Australian Government
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Defence Science and
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Some Aspects of Submarine Design Part 1. Hydrodynamics (U)

Prof. P.Joubert

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ABSTRACT

The history of submarines shows there were two significant advances in the performance of submarines, which occurred after full scientific studies were undertaken. The first was by the Germans at the end of World War II when they produced the Type 21, which could have upset the balance in the U-Boat campaign if it had arrived earlier. The second was by the US Navy with Albacore which had a submerged speed of over 30 knots. To neglect full scientific studies would be a serious mistake in the design of any future replacement submarine. Design is shown to be like a jigsaw puzzle where altering one piece requires alterations in all surrounding features to make a workable complete design. The basis of improved hydrodynamic features is discussed. A new nose shape is presented which should improve the performance of the forward passive sonar up to operational speeds. Other major sources of resistance may be improved. It is proposed a first major step should be to establish the detailed performance of Collins using wind tunnels and computational fluid dynamics which will serve as the comparative foundation for any new design.

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Some Aspects of Submarine Design
Part 1. Hydrodynamics

Executive Summary

The history of submarines subsequent to the first truly operational vessel, Holland, launched in 1899, showed two significant advances as opposed to steady incremental developments. These resulted from full scientific studies of all the problems. The first of these advances was made by the Germans at the end of World War II, when they produced the Type 21 which had major improvements in range and battery time while their underwater speed increased to 18 knots compared to 5 knots on previous vessels. Design diving depth was increased dramatically. They could operate below the Allies submarine defence weapon systems. The second advance was made by US designers who produced Albacore in 1953 with a shape suited to full underwater operation. Its length-to-beam ratio was only 7.7 and top underwater speed was 33 knots. The drag coefficient was only 0.1 compared to 0.35 on previous submersible designs.

It is clear that scientific studies should be a starting point for any future submarine design. A review of the literature covers priorities in design and shows how enhancement of one feature interacts with other features and may even result in an overall loss of performance despite the perceived advantage of the enhanced feature. Hydrodynamic aspects are then discussed starting with the shape and reasons why a length-to-beam ratio of about 7.5 gives the minimum resistance. All features affecting the resistance are discussed including the boundary layer, laminar flow, transition, turbulence and separation and how the flow over the principle passive sonar should be as quiet and smooth as possible. Added resistance from sails, masts, snorkels and appendages need careful streamlining and attention in design. A proposed profile of a new submarine is presented which has the passive sonar far forward in the streamlined nose with the torpedo tubes positioned further aft. It should be a quieter vessel with more effective sonars. The profile requires shortening to reduce the displacement and then the internals need rearranging. The design process then begins, which is iterative.

In order to proceed with such concepts it is vital to have a database. Our current submarine, the Collins class, should be the base from which all changes and proposals are measured. It is suggested detailed wind tunnel studies should be undertaken concurrently with computational fluid dynamic (CFD) evaluations. The results should then be compared with full scale trials to establish propeller efficiencies and roughness factors as well as the contributions for each feature, hull, sail, control fins, masts and snorkels, flood openings and others. This database will allow more precise comparisons for any improvements which may be considered in a future design.

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P.N Joubert, a World War II fighter pilot, after demobilisation from the RAAF, studied aeronautical engineering at Sydney University. He then joined CSIRO, where he designed a radio controlled meteorological glider. Subsequently he was appointed as a lecturer in mechanical engineering at Melbourne University specialising in fluid mechanics. In 1954 he attended the MIT where he built and tested high-speed catamarans in the towing tank. At Melbourne University he built a new wind tunnel and much research was initiated and conducted there. He has authored over 120 scientific papers, most of them in fluid mechanics, boundary layers, roughness, and vortices and recently with a PhD student, the flow about a submarine body in a turn. Over the years he has received many research grants including one from the US Navy. His work with his students and colleagues is recognised internationally such as by the General Motors Research Laboratories and other international ship research bodies. He has been studying flow patterns on submersibles since 1998 and has helped with certain modifications to Collins. In 1972 he was granted a personal chair and since retirement has been invited to continue as a Professorial Fellow. He was awarded a medal in the Order of Australia in 1996 for contributions to road and yacht safety. He was awarded the AGM Michell medal in 2001 by the College of Mechanical Engineers and is a Fellow of the Australian Academy of Technological Science and Engineering. As a yacht designer he has had over 100 yachts built to his designs, including a high-speed catamaran for the world sailing speed record and ocean racing yachts. Some of these have won against world-class competition – the Sydney-to-Hobart race in 1983 and second places in 1968, 2002 and 2003. As a sailor he has raced his own designs in 27 Sydney-to-Hobart races and survived the storm of 1998. In 1993 he was awarded the Commodore's medal of the Cruising Yacht Club of Australia for outstanding seamanship after his crew had rescued eight survivors from a sunken yacht at night in a strong gale.

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1. Introduction

The following is a study on submarine hydrodynamic design, with emphasis on future concepts for Australian submarines.

2. Brief History

Any study should begin with an examination of what has occurred in the past, otherwise one can end up reinventing what is already known or even ignoring critical information. It is important to understand the reasons for the shape of submarines at different stages of their development and why changes were made. Important phases in development will now be outlined.

Submarines have existed as early as 1776 with Bushnell and his Turtle followed by Fulton and his Nautilus in 1800. These American vessels, designed to beat the British blockade, suffered from lack of a suitable power plant, which was overcome later by the inventions of both the internal combustion engine and the battery.

2.1 Holland

A major improvement was made in 1899 by an Irish American schoolmaster, John Holland, with his design "Holland", which included many of the features of modern submarines. It was no mean vessel displacing 63 tons, a length overall of 53 feet (16.2m) and a submerged speed of 5 knots (2.6 m/s). Its range was 1500 nautical miles (2,778km). There was an aft propeller with control vanes for steering. Its general proportions were not that different from the later, more sophisticated "Albacore". Its profile was streamlined, a small rounded nose increasing to the full cross-section followed by a tapering tail. Its length to breadth ratio of 5.05 was a little full but not far from the optimum.

Because of its need of oxygen for combustion, the petrol engine could not be used when the submarine was submerged. However, when the craft was on the surface and the hatch open, the engine could operate a generator to recharge batteries and it could also then propel the ship. Then it suffered from water entering through the open hatch due to the low freeboard, which prompted the addition of a larger raised conning tower in later designs.

A single propeller was arranged at the tail with control vanes, a rudder and elevators. An elevation and plan of a later Holland is shown in Figure 1.

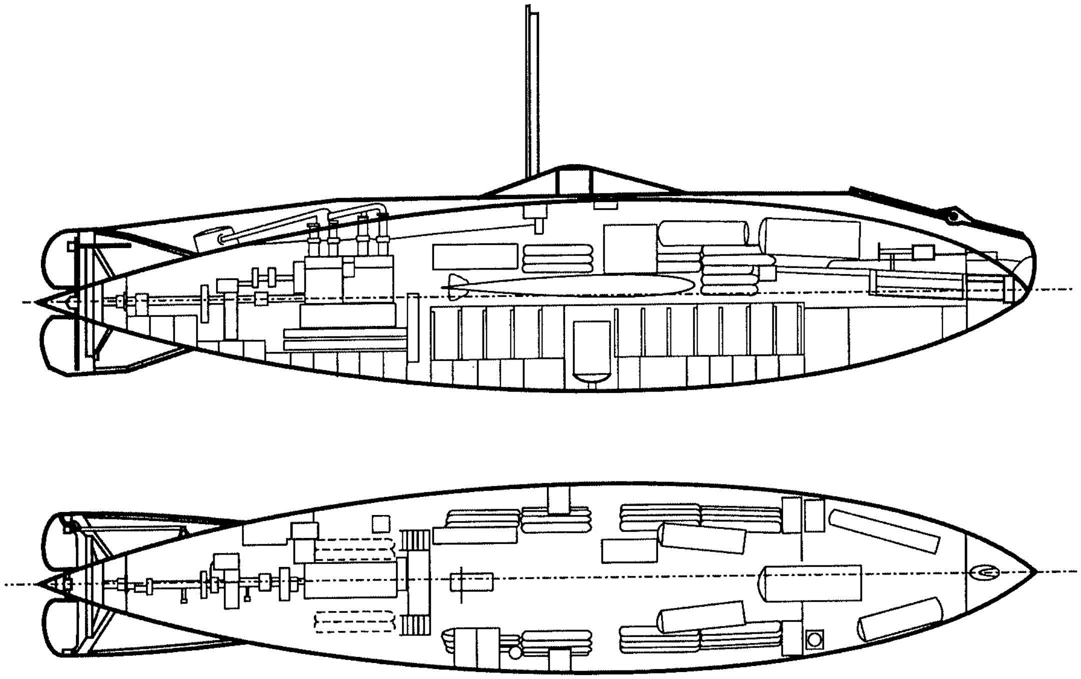


Figure 1. Profile of Holland [7, p.11]

A copy of a 1900 photograph shows the bow view and the steering position from which the boat was navigated while just awash. The bulbous protrusion spoils the otherwise ideal streamline shape. (Fig. 2.)

Figure 2. Bow view of Holland [7, p.10]

2.2 Protector

A second American inventor, Simon Lake, independently arrived at the solution, combining the petrol engine and the battery. His vessel, Protector, was launched in 1902. His greatest contribution was to overcome the problem of sight because submarines when submerged were blind. With the aid of a professor of optics, from John Hopkins, they constructed the forerunner of the periscope. Lake's submarines were sold to Russia and Austria. Later they were bought by the US Navy, as were those of Holland.

2.3 Diesel Engine

Although the submarine could now see when submerged and could travel considerable distances, there remained one dangerous problem. Petrol fumes were ever present within the hull with all the chances of a catastrophic explosion. The problem was solved by the invention of the compression ignition engine by a German engineer, Rudolf Diesel, in the 1890s. With no electric spark and running on cheaper, much less volatile fuel oil, the diesel engine, as it was called, was more efficient and more economical giving greater range. Far more important, the fumes were less toxic and volatile. Henceforward it became the accepted main source of power until the advent of nuclear power.

2.4 U-boats

World War I accelerated progress in the design of submarines. The German navy developed its long, heavy, long ranging, diesel powered Unterseeboote or U-boats, as they were known through two world wars. They were essentially surface running ships with fine bows and usually mounting a gun, a large bridge fin and superstructure, underslung twin propellers, many excrescences and innumerable flooding and venting holes for rapid surfacing and submerging. No attention was paid to underwater performance. The U-35 is typical of the type (Fig. 3).

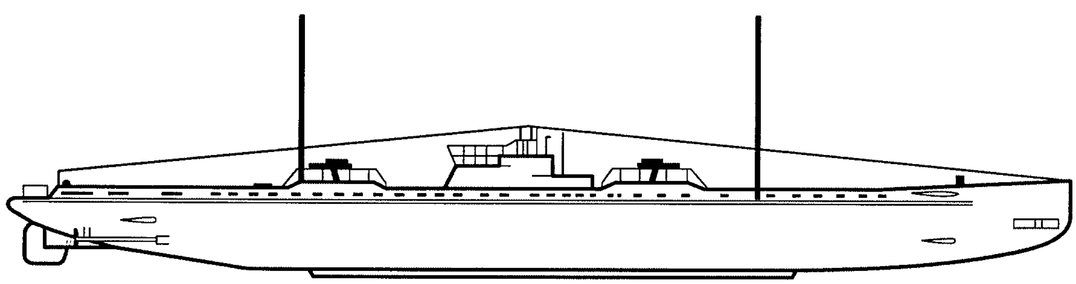


Figure 3. U-35 Typical of Word War I Submarine [1]

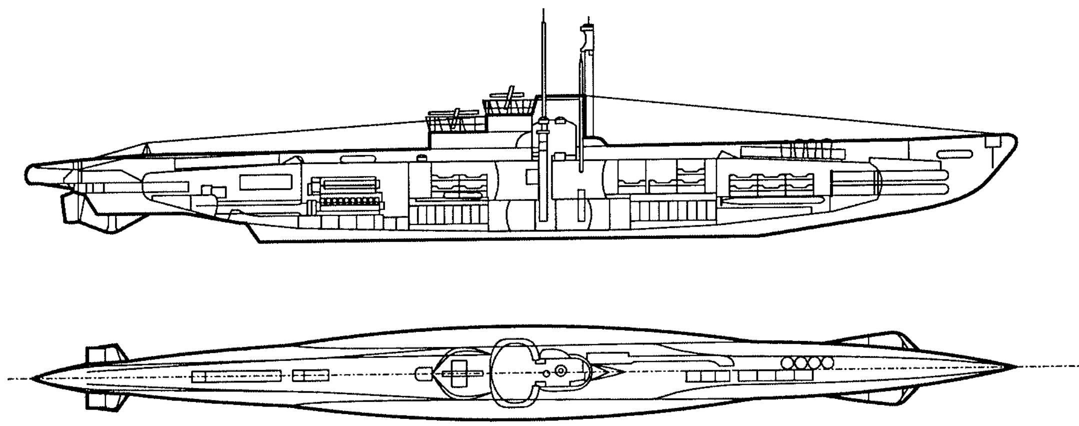


Figure 4. Type VIIC. Typical of a World War II German Submarine [11]

Germany entered World War II with a more refined version of submersible, still not a genuine submarine, but with its characteristic emphasis on surface performance (Fig. 4).

2.5 Snorkels

Snorkels were introduced in about 1944, conceived by the Dutch and taken over by the conquering Germans, they helped U-boats to survive the Allied sub-hunters. But they were not without their problems. If the intake dipped below the surface a valve would shut and the diesels would gulp air from the hull creating a partial vacuum that could affect the crew. The trim of the boat was delicate. The problems remain, especially that of detection when snorkelling.

2.6 Type 21

In response to the mounting U-boat losses in 1943, a submarine research centre was created by the Germans at Blankenburg in the Harz Mountains, with the aim of producing an operational high-speed U-boat capable of prolonged submergence.

The Type 21 that resulted represented a compromise since it was aimed at AIP using hydrogen peroxide and the Walter propulsion system, which had not then advanced beyond the experimental stage. Coupled with the scarcity of hydrogen peroxide, the designers adopted enhanced diesel-electric power. The hull was dramatically streamlined removing the exposed gun and any external feature that would heighten resistance as well as reducing the size and profile of the conning tower (Fig. 5). Range and battery time were improved and underwater speed was raised to 18 knots, over 10 knots faster than before. Their design diving depth was improved dramatically. They arrived too late for war service.

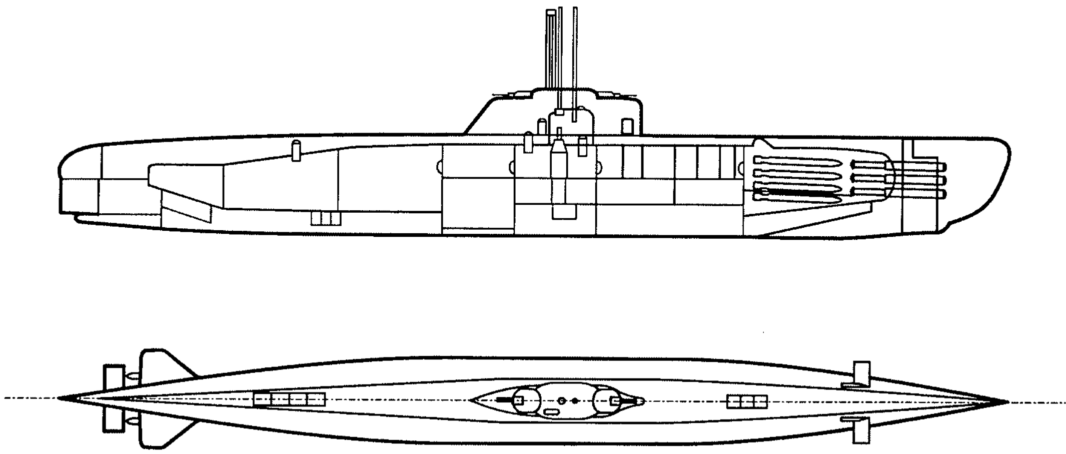


Figure 5. U21 [11]

2.7 Albacore

Following the end of World War II both the British and United States Navies acquired some Type 21s for evaluation. They were amazed at the advances in the German boat. The United States then played "catch-up" and the Bureau of Ships adapted the extremely successful American fleet submarine of World War II for greater underwater speed by streamlining the hull and conning tower, removing all appendages - including the guns - and dramatically increasing the battery power. The submerged speed increased from 8.75 knots to 18.2 knots [3].

They went even further in copying the German approach. In 1948, the Committee on Undersea Warfare of the National Research Council initiated an effort to accumulate the collective wisdom of the naval and scientific communities on the hydrodynamics of submerged bodies. Out of this evolved the design of Albacore with a shape giving the minimum underwater resistance based on the best available hydrodynamic research.

A larger single screw, slower revving propeller provided the best propulsive efficiency. The control arrangements were varied in a number of modifications to give the shortest turning circle. Most importantly, the sonar was later placed in the streamlined nose for maximum effect [3]. Snaproll was reduced by trialling an adjustable trailing edge flap on the fin. The fin was made as small as possible in order to reduce drag (a streamlined fin represents about 25% of the total drag). The length-to-draft ratio of Albacore was 7.723, which compares to Collins at 9.96.

A paper describing the design was presented by Captain Jackson at Warship '96 [4]. A chapter in the SNAME publication [3] on American submarine development is equally illuminating. Albacore on batteries reached a submerged speed of 33 knots and a surface speed of 25 knots. Its radical diesel engines with a vertical crankshaft produced more

power per unit weight than before, but were unreliable. The vertical arrangement required less critical longitudinal space and they developed 15,000 SHP. The large single screw showed a remarkable propulsive efficiency of 0.9 [7, p. 139].

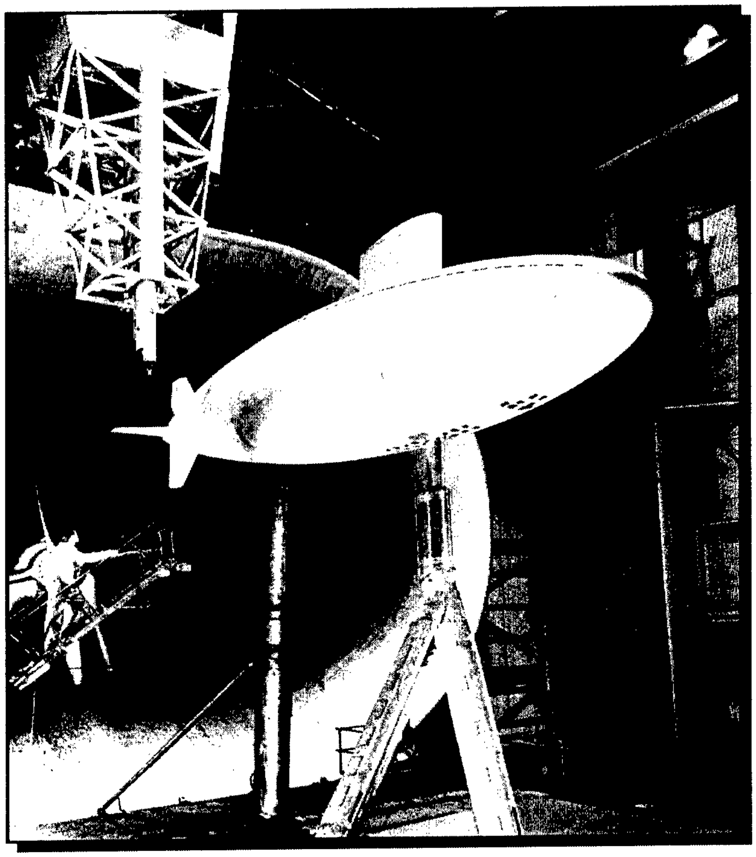


Figure 6. Albacore being tested in a wind tunnel [7]

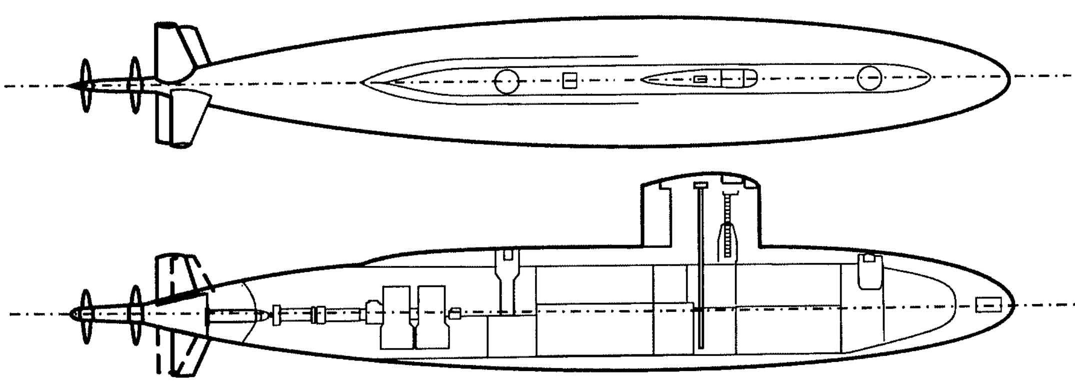


Figure 7. Albacore (4th Modification) [4]

2.8 Barbel

The Navy applied the results of its research with Albacore to an operational vessel called Barbel in the late 1950s. Save for nuclear power, these diesel electric vessels had almost everything that the latest knowledge of hydrodynamics and modern technology could provide. Barbel was the first operational submarine to have the Albacore hull design, a single most efficient propeller on the axis, an advanced ballast control panel and HY-80 hull steel. She displaced 2,145 tons with a length-to-draft ratio of 7.55 and could make 21 knots submerged.

The paper by Captain Jackson [4] provides most interesting reading and shows arrangements of Barbel (Fig. 8).

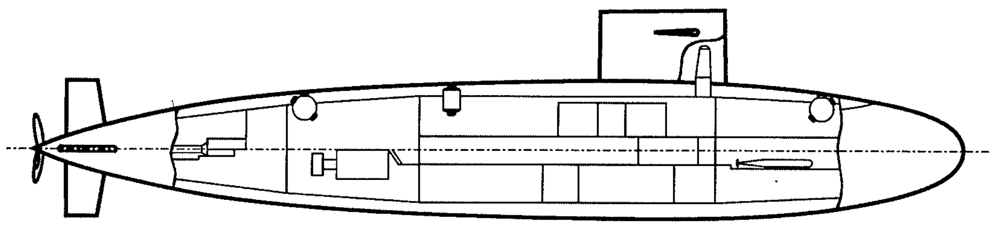


Figure 8. BARBEL profile layout [11]

2.9 Skipjack

This led, with the success of the first nuclear powered submarine, Nautilus, to a milestone in development, Skipjack. Albacore had demonstrated that a pure underwater shape (with obvious disadvantage for surface travel) was operationally acceptable because of its improved submerged performance, better handling for underwater course and depth control and for manoeuvring. In trials she proved a spectacular success. Easily, almost lazily, she travelled at the speed of the fastest fleet submarine on one quarter the power. Her advances in controllability were so remarkable that her officers coined the word "hydrobatics" to describe her stunt-like manoeuvres. She not only turned and banked like a plane but could even make the tight climbing turn that flyers call a chandelle [5]. The helmsman sat in a seat with straps like a pilot controlling a joystick as in an aircraft.

Nautilus, apart from the power, was in other respects relatively conventional in form and arrangement. Its main purpose was to demonstrate how the pressurised water reactor stood up to sea service. Its range became unlimited and it had no need to surface or take in oxygen.

Skipjack combined the nuclear power with the underwater teardrop streamlined shape of Albacore. It was substantially less in displacement than Nautilus with the same installed power giving even higher underwater speed and greater manoeuvrability.

Skipjack had a number of the same proportions as Collins (), namely, a displacement of 3,075 tons (3,050) surfaced, 3,500 tons (3,353) submerged, LOA 251 feet (255). However the beam was greater, 31.5 feet (25.6) and the proportions were about ideal, L:B=8.0 (9.96). The draft was less different, 25 feet 3 inches on Skipjack compared to 23 feet on Collins. The installed power of 15,000 HP as against 6,000 HP in Collins was 2.5 times greater. A distinct advantage of the greater hull diameter was the number of decks, four in Skipjack, giving so much more usable and discretionary deck area [12, p. 637].

2.10 Beyond Skipjack

Later designs, in order to accommodate the largest number of ICBMs (Intercontinental ballistic missiles), grew in length and displacement and no longer maintained the ideal relationship of form or cross-section for minimum resistance, a probable reason being the limitations on channel depths in berthing harbours and for dry docking [8,12 p. 637].

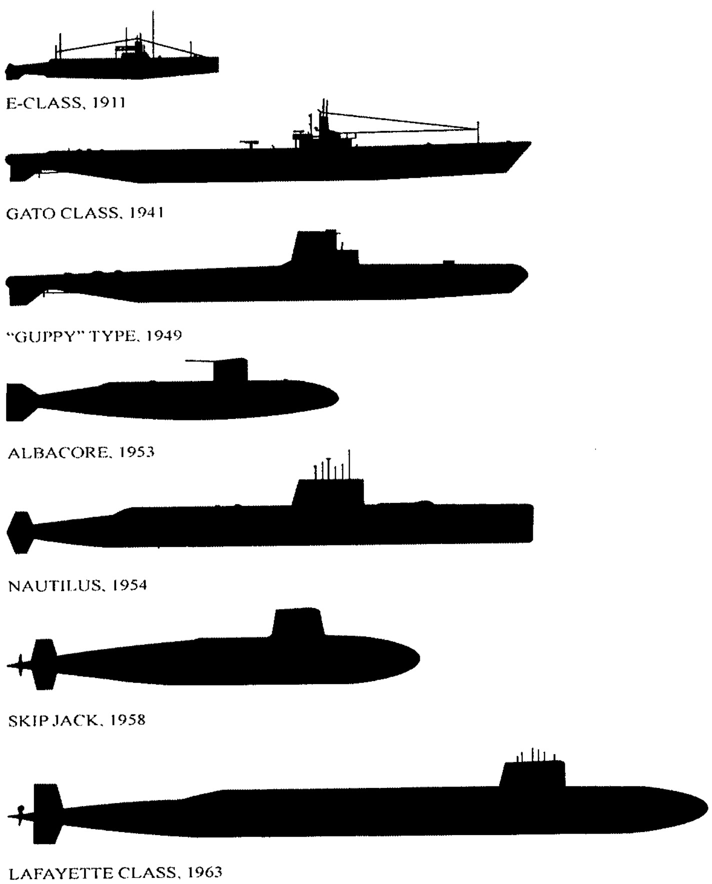


Figure 9. Evolution of submarine design [5, p.132]

Profiles of US submarine development are shown in Figure 9. The very large Lafayette Class was eventually outmatched in size by extreme Russian designs, which have produced their share of problems. In order to achieve this higher displacement and probably for berthing, the Russian vessels were no longer circular in cross-section. The

Typhoon Class were 560 feet (170.7m) in length, 80 feet (24.4m) in beam, 42 feet (12.8m) draft and displaced 18,800 tons when surfaced and 27,000 tons when submerged [6].

There have been numerous smaller SSKs designed and built, a number of them with very blunt noses and this feature will be discussed in detail later in this report.

2.11 Comment

Following the initial successful independent designs of Holland and Protector, progress followed from technological advances and appeared to be stagnating until the Germans adopted the full scientific approach to produce the Type 21.

The Americans made an even greater advance when they adopted the scientific approach and produced Albacore and Skipjack. To neglect scientific examination of any future submarine may be a mistake.

3. The Design Approach

3.1 Interactions

It is a principle of successful design that no particular feature can be considered in isolation but must be considered with all its interactions on the rest of the design.

It has been my experience that whenever the designer loses control of one of the interacting features, it may result in deterioration in the overall desired outcome.

Experienced Russian submarine designers comment that most submarines constructed during the last quarter of the 20th century can be characterised as demonstrations of single purpose innovations [9]. Their comments continue, "While significant, the implementation of these technologies generally resulted in single function enhancements, often to the detriment of other functions or performance characteristics", which is a better expression of the point I was trying to make in the opening paragraphs. They continued, "Often such an approach leads to deterioration in other individual capabilities, an increase in cost and excessive displacement." The integration of selected new technologies to improve overall system efficiency and affordability is the achievement that will characterise the more capable, yet still affordable submarine systems that will be introduced during the first two decades of the 21st century."

Burcher and Rydill [1], think of design as a layered pyramid with the role of the new design and a description of its tasks forming the apex. They discuss the interaction of each feature of the design on all the other features and for success they must fit together like a jigsaw puzzle to make a complete and efficient design. If one piece is altered so that it no

longer fits then immediately adjacent pieces have to be altered to allow it to fit and this process may continue with an unfavourable result.

Having made the point about integrating features in design, it follows this report will not be completely confined to considerations of hydrodynamics, but will attempt to consider some of the interactions.

4. Priorities in Design

4.1 Introduction

These priorities will force the design with regard to internal volume and all that is needed on-board, the range will determine the fuel load, the operating depth will determine the strength, the technology will play a large part in determining the crew requirements, the feeding, accommodation and thus the interactions will have to be fitted into the jigsaw.

4.2 Operational Tasks

The Vice President of the Royal Institute of Naval Architects, G.H.Fuller, in delivering his 1999 paper [20], lists the following operational tasks:

- Acoustic, visual and electronic surveillance of adversary
- Supporting SEAL reconnaissance and intelligence missions
- Shore bombardment
- Trade blockade
- Mine laying
- Minefield identification and clearance by divers
- Anti submarine warfare
- Protection of surface forces
- Defence against covert and overt surveillance
- Efficient, fast and secure communication with the national command, military, political and local force commanders.

The Russian designers [9] list certain priorities for the next generation of submarines namely:

- Secrecy, including reduced magnetic, electric, thermal, radio frequency and hydrodynamic detectability as well as acoustic quietening.
- Offensive and defensive weapons in combination with information systems
- Manoeuvrability and high propulsion qualities (high speed at low power expenditure).
- Durability (the ability to sustain damage and remain effective)
- Cost

In discussing acoustic quietening, apart from machinery and internal generated noise, they mention propeller and hydrodynamic noise.

G.H.Fuller in delivering an earlier paper in 1996 [10], concluded that new design concepts must include: "

- An operating depth of no more than 200m
- Very long high speed transit capability followed by long, silent covert deployment on station
- A coherent approach to survival
- Low maintenance materials and equipment, easy hull access.
- A more cost effective build procedure learning from best offshore and engineering practice.

Professor Andrews [15] suggests multi-role capabilities of, Special Forces delivery, communications bases and sub-surface land attack missile carriers, and this implies different configurations with even modular fits (plugs) being contemplated.

The French position as outlined in [17], had the objectives of:

- Permanence at sea
- Lowest vulnerability both in transit and on patrol
- Efficiency from the first day of the mission to the last
- Capability at all times to make a decisive attack and to survive it
- Minimisation of the crew in order to minimise investment in personnel.

The German position is not so clearly put, but two early papers by Winkler [18] and Saegar [19] are of interest.

Winkler discusses the improvements that have occurred since the Type 21, namely:

- Greater diving depth (factor 2-3 times)
- Higher speeds due to better hull form and stronger electric motors
- Greater submerged cruising range due to better batteries
- Lower rate of indiscretion (snorkelling time: submerged cruise time)
- Improved passive protection by reducing noise emission and better shock resistance
- Improved weapons from sensors to torpedoes
- Improved safety due to new rescue concepts

The future priorities are not listed as such but the discussion more or less points the way ahead.

Saeger likewise does not list priorities but he seems to be considering a different role to that of an Australian submarine. His example suggests a range of 6400 nautical miles as the maximum. His company is developing fuel cells.

Fuller [20] states that the end of the cold war has seen the end of superpower confrontation contained by the nuclear deterrent and the advent of many local conflicts. This requires a shift of major assets from battle groups and logistic sea-lanes to power

projection in the littoral and refers to the United Kingdom Defence Review of 1998. The shift is complete but also has to address the asymmetric threat, which now dominates most requirements exemplified by land strikes and air operations such as in Kosovo and Iraq.

He suggests the littoral is not a soft option, it is a very multi-mission area at all levels from relative peace to hot war. The threats are multi-facetted. Sea control will be looked back as a simple, single mission task.

He concludes that the new operational requirement for covert and overt warfare in a hostile environment sets many new problems to solve. A critical question is the need for small size, it is a good in itself, necessary for safe operation in restricted waters. But it must not be an arbitrary size, set in the hope of achieving a given unit cost, whatever the effect on capability and minimum through-life cost.

A thought provoking paper was presented at the Warship 99 conference by two Americans, Whitcombe and McHugh [21]. They are advocates of plugs as was Professor Andrews [15]. They point to three incidents:

I. The risk to the Falklands task force posed by a single SSK and the asymmetric impact on naval deployment,
II. North Korean submarine penetration of South Korean coastal defences, and
III. The near sinking of a US Warship in the Persian Gulf in 1987 illustrating the lethality of anti-ship missiles. Two Exocet missiles hit the ship; they were air launched, however they could have been fired from a submarine platform.

While these three incidents illustrate the asymmetry, stealth and potency of present day SSK submarines, new technologies can increase the potency of these boats. (Asymmetric refers to the situation where a disproportionate amount of an asset must be used to counter a threat.) The ability to launch longer range cruise missiles for precision surface strikes enhances the role of the SSK.

They suggest the potential exists for a paradigm shift in submarine warfare capability through the combination of strike missile development and AIP systems.

Admiral Hervey [14, Ch. 2] discusses the roles of submarines and in part their role in the Falklands campaign. He says, "Maritime Forces are employed to ensure that our own surface forces can continue to use an area, or to deny its uses to enemy surface forces. Submarines can have offensive and defensive roles in support of both strategies. They may work in coordination with other friendly forces, but can also be sent into areas where no one else can go or where it would be embarrassing for them to be seen. In all roles, they may be pitted against either ships or other submarines. And for both, they remain one of the most dangerous opponents."

Friedman [47, pp. 212-214] discusses the thinking of US naval commanders. The discussion is too long to include here but it led to a 6,000 - 8,500 ton vessel nuclear

powered but less expensive than Seawolf. A non-nuclear vessel was also considered with an AIP auxiliary plant for loitering. Modular sections were considered with variants for special operations, electronic warfare, mine warfare, land attack with missiles and sea control and maritime surveillance. It was even suggested such a vessel could replace an aircraft carrier.

4.3 Area of Interest, Range and Transit Time

One might assume that the role of a new Australian submarine might not be that different from that of Collins but with every aspect improved in efficiency and up to date with current technology. An Australian submarine might be required to travel from its base in Western Australia as far west as say, the Arabian Sea and as far North as the China Sea, which gives a round trip of over 10,000 nm (nautical miles) plus time on patrol without refuelling. So a range of over 12,000 nm might be required. Collins as is mentioned in Janes [13] had a range of over 10,000 nautical miles. A transit speed of 12 knots over two weeks would be required to reach the furthest operational area, an unduly long time.

Seven days might be more acceptable requiring a doubling of cruising speed. Even with the most perfectly streamlined boat, with the smoothest surface, no roughness whatever and the smallest low drag appendages, this does not appear feasible with current types of powering.

4.4 Speed

While speed has been mentioned under travel time, Fuller [20] specifies two criteria; maximum quiet speed and "noisy" high top speed for transit and escape from attack respectively. Here he could well be talking of a nuclear powered vessel. He continues, "Whilst both have their place, the need to loiter and be undetectable is vitally important. The power plant must be stable at these very low powers and create no noise or wake when changing speed."

Transit speed is another feature composed of part snorkelling and part fully submerged battery powered operation. Then the snorkelling speed cannot be too great, being limited not only by the drag, the vibrations and wake signature left on the surface, but also by the power available to recharge the batteries and the exposed time. Consequently the snorkelling speed is reduced well below the maximum.

4.5 Diving Depth

Depth to which the submarine may operate plays a crucial role in design. The deeper the operating depth the stronger the hull has to be built and the more weight is proportioned to the structure leaving less available for all the other requirements like fuel, armaments, machinery, etc.

There are a number of depths; collapse depth, safe depth and working depth. It is undesirable to make frequent dives to safe depth because heavy working of the hull ages it prematurely [14, p. 19]. A factor of safety applies between the collapse depth and the safe depth (sometimes called maximum designed operating depth) which may be 1.5 or higher and provides a margin of safety which takes care of the inaccuracy of calculations of strength of the indeterminate structure; the departures from the designed shape; stress concentrations from holes; to provide against fatigue; imperfect workmanship; reductions due to corrosion; dynamic loading and inadvertent travel below safe depth [23, pp. 633-634]. Design depth also affects combat and weapon system parameters and escape and rescue philosophy.

The littoral is contained in the continental shelf where the seabed sets a floor of about 200m. Fuller [20] questions whether it is worth having a design depth greater than 200m. He also comments on the need for excellent depth control in water depths less than 50m to ensure no chance of broaching. The Russians [24] refer to a diving depth of 300m.

Miller and Jordan [28, p. 44] show typical diving depths of current submarines. The Los Angeles class is shown with an operating depth of 450m, the French Rubis Class 300m and the titanium hulled Soviet Alpha deepest at 700m.

Norman Friedman [47, Appendix C] in his later book on U.S. submarines shows the test depth of various designs (presumably "test" is synonymous with "safe").

4.6 Further Priorities in Design

Fuller [20] refers to further priorities, some of which will be discussed later, but are simply listed under this heading:

- Passive defence
- Combat systems
- Escape and rescue
- Resupply
- Maintenance
- Crew Size

Choice of power plant would also be a major priority in design together with:

- Hydrostatics and weight balance
- Structural design
- Dynamics and control
- Submarine systems: pneumatic, hydraulic, electric and electronic

Admiral Hervey [14] writes succinctly and to the point on hull size and shape. "A submarine, tear drop shaped, inside which are one or more pressure hulls for strength and depth range, external main ballast tank (MBT) to change role from surface ship to submarine and internal tanks to maintain neutral buoyancy underwater. The hull size depends primarily on the weapons to be carried but also on: the number of men to be

embarked, the length of patrol intended and, for an SS, the distance the fuel has to carry the submarine before refuelling. At the design stage, there is very little room for error over weights, volumes or dimensions, one of the most difficult calculations being the positioning and size of the fin. At the building stage, everything depends on quality control."

This preliminary discussion is not intended to be a designer's handbook and will now continue with that subject where the author is positioned to make a possible contribution.

5. Hydrodynamic Design

5.1 Shape

An important variable in determining hydrodynamic performance of a submarine is the length (L) to beam (B) ratio. From a lot of research which led to the design of the first real submarine (and not a submersible) namely the Albacore, an L:B ratio of 7.723 was chosen as being about optimum.

This follows from the variations in two different kinds of resistance, which together make the total resistance of the basic body of a fully submerged submarine. The first kind is called form drag or pressure drag.

The pressure acts at right angles to every point of the surface. The pressure varies along the surface being greatest at the nose, the stagnation point, about which the streamlines divide. The pressure is least where the streamlines are closest together and rises where the streamlines are diverging (Bernoulli's Equation). In a fluid with no viscosity the pressure right at the tail would rise to the same value as that at the stagnation point on the nose; then the integral of all the pressures acting on the elemental areas (the pressure forces) would be zero i.e.

$$\oint p dA = 0 .$$

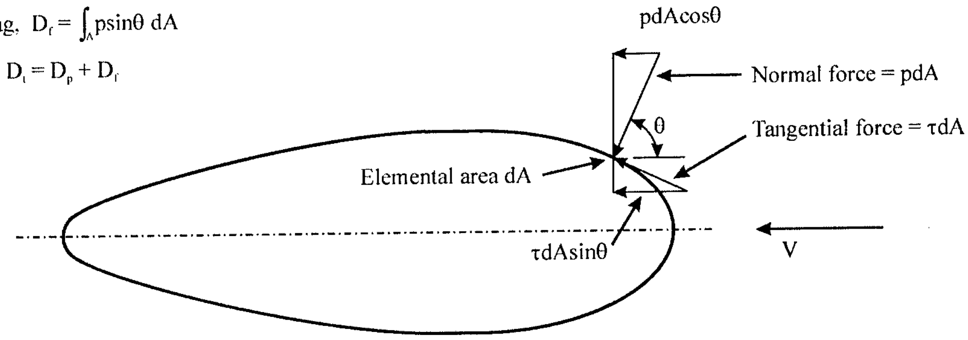
However, the fluid does have viscosity and this property gives rise to the tangential forces or skin friction. The boundary layer, while initially quite thin, thickens towards the tail and streamlines do not diverge as wide as they would in an inviscid fluid, which effect causes the form drag. The virtual shape of the body has been altered by the boundary layer and can be evaluated, mathematically, by the law of continuity.

The two kinds of drag, that from the normal forces and that from tangential forces (form drag and skin friction) are about equal in value on a streamlined body. As the L:B ratio increases, the body becomes longer and more slender and the form drag decreases.

Pressure drag, $D_p = \int_A p\cos\theta \, dA$

Friction drag, $D_f = \int_A p\sin\theta \, dA$

Total drag, $D_t = D_p + D_f$



The components of the two forces in the direction of the velocity, V, give the drag on the elemental area.

Integration gives the drag on the body.

Figure 10. Components of drag on a submerged body

The second kind of drag, the skin friction drag is proportional to the wetted surface, so a long skinny submarine would have more wetted surface than a short fat one of the same displacement. The variation of the two kinds of drag and their summation when plotted against the L:B ratio for constant volume is shown in Figure 11.

There is clearly a minimum in total drag at an L:B ratio of about 7 but the curve is flat in this region. There is no precise minimum.

The above discussion considers the bare hull and does not include the sail (fin), control surfaces, and interference drag at their joins to the hull, extra protuberances like towed array fixtures and other drag creating features.

In his 1983 paper, R.J.Daniel, Managing Director Warship Building, British Shipbuilders [16], states "for a solid-of-revolution form, zero parallel middle body is associated with minimum residual drag and the effect of reducing the length:diameter ratio is to decrease surface area and hence skin friction resistance down to the optimal ratio of about 6, with a prismatic coefficient Cp of about 0.6."

These are the laws of physics and should be the aim of any new design. Further on it is interesting to note his comments,

> "c) The roughness of the hull can significantly effect resistance. The roughness allowance for a badly prepared and painted hull, with badly positioned and shaped flood openings would be several tens of times larger than for one with an optimal finish.
>
> d) The resistance due to appendages no matter how streamlined and carefully executed, approaches and may exceed, 50% of the bare hull resistance."

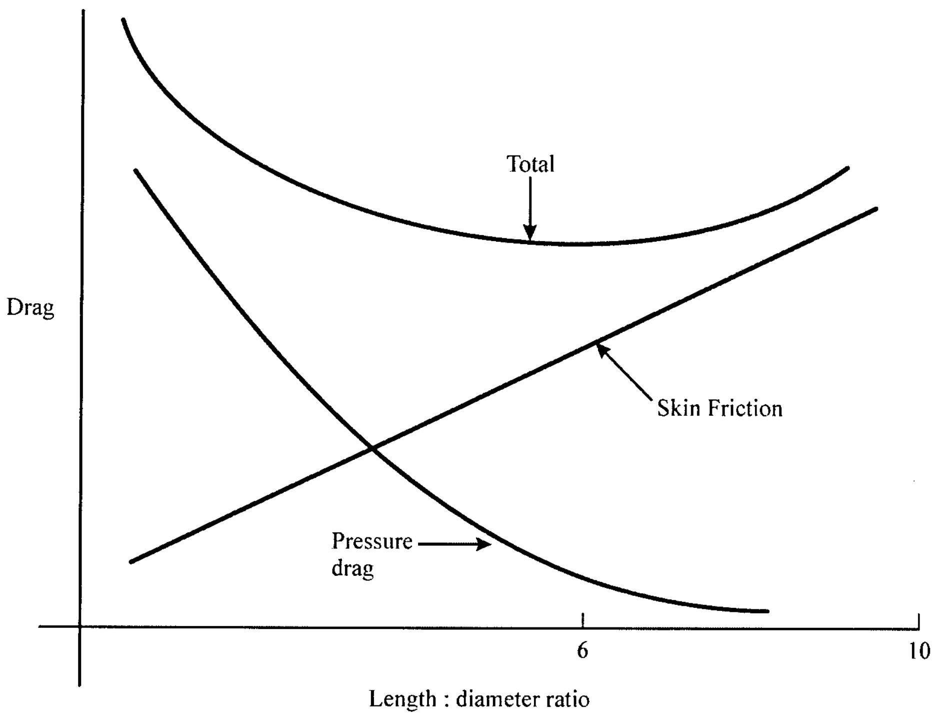
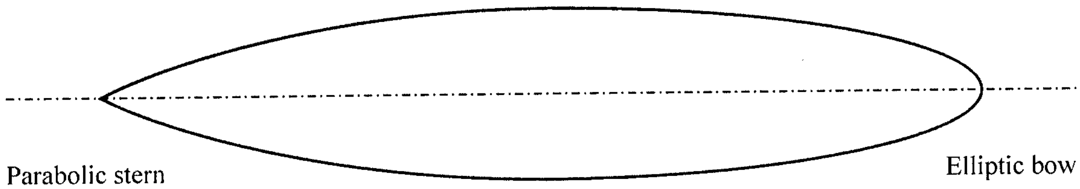


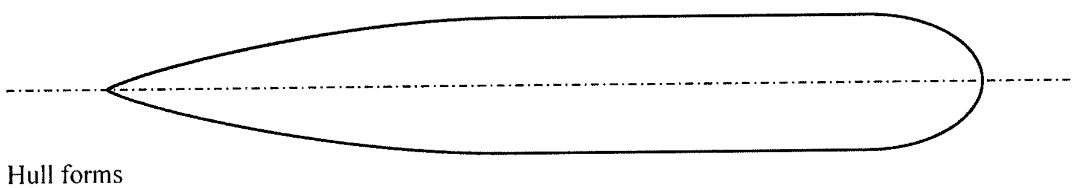
Figure 11. Drag components for constant volume form [1, p.105]

A second parameter, which influences resistance of the streamlined body, is the prismatic coefficient, Cp. This parameter describes the amount of volume in the ends of the hull. Collins for example would have a coefficient at the high end of the scale (estimated as greater than 0.8). Albacore had a Cp of about 0.65.

The ideal form involves a continuously changing diameter along its length. The bow would be ellipsoidal and the stern paraboloidal in shape [1, pp. 104-109; 12, pp. 628-632]. A modest departure from this ideal with a portion of parallel mid-body would reduce the draft and the building costs by positive amounts without any severe drag and noise penalties. Severe departures from the ideal form would not only increase the drag and the noise but also impose both speed and range limitations. The added fuel costs over the lifetime of the submarine as well as the greater chance of detection for the high prismatic vessel need to be balanced against any savings in building costs by having a cylindrical shape (Fig. 12).



(a) Ideal form



(b) Parallel midbody form

Figure 12. Hull forms

Arentzen [12, Fig. 4.] shows the variation which occurs in residual resistance coefficient (form drag coefficient) with change in prismatic coefficient. As well, the effect of varying relative lengths of parallel mid-body is shown. Increasing the length of parallel mid-body does increase the form drag, but a small amount does not have a great effect. It reduces the draft and Skipjack appears to have a certain amount (about 12.5%). Barbel has even more length of parallel mid-body.

The Russian submarine designers [9] express concern that many smaller European submarines cruising at 10 knots will be expending up to 400kW more power towards the production of wake fields than a well-formed submarine. What they are saying is that properly shaped bodies have less drag compared to other shapes. However there are certain advantages by having some parallel mid-body such as deck space, less initial cost and draft limitations. So a new version of Collins might look like the profile shown.

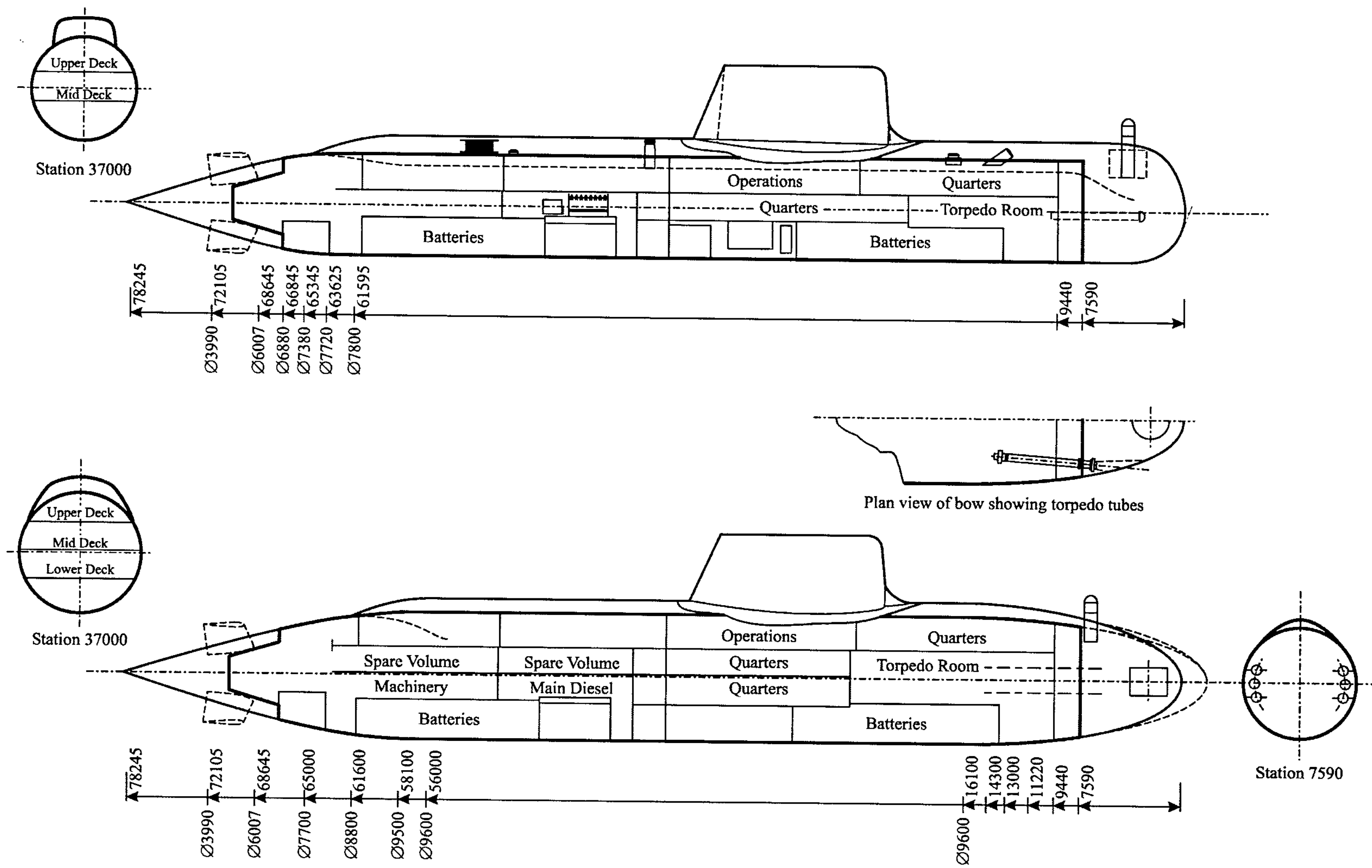


Figure 13. Profile of Collins Class submarine and a future submarine concept

Note that with B now 31.5 feet (9.6m) compared to Collins at 25.6 feet (7.8m), the draft is 25.3 feet (7.7m) compared to Collins at 23 feet (7.0m), which should be manageable, especially as the new boat will be less sensitive to bow down trim. The further great advantage with this increased beam dimension is the fitting of four decks over portion of the length as with Skipjack. This will give more flexibility to the design [12, p. 637] and allow for change in activities without the costly and time consuming modular design solution suggested by Andrews [15]. (See comments in Appendix 6)

Fuller [20] comments that, "the shape and configuration of the hull envelope is the critical starting point. The need to be energy economical and reduce target echo strength means a return to the optimum shape".

Admiral Hervey [14] comments on hull shapes, " The pressure hull cylinder and MBT must be encased in a free-flooding, well streamlined outer shell which has a shape optimised for high underwater speed, low length to beam ratio (less than 8:1), bulbous bow, maximum width at about a quarter length from the bow and then tapering almost to a point at the stern." His figure 3.9 does show a shape with quite a reasonable prismatic coefficient and it could easily have some parallel mid-body without measurable effects.

It is noted that Ulrich Gabler, the father of submarine design [11, p. 13], states that Japan has built 14 submarines resembling Barbel. His book was published in 1986 so these boats would belong to the Yuushio Class, first launched in 1979. The improved Harushio Class has followed them and this seems on the face of it, an ideal shape with a greater length of parallel midbody.

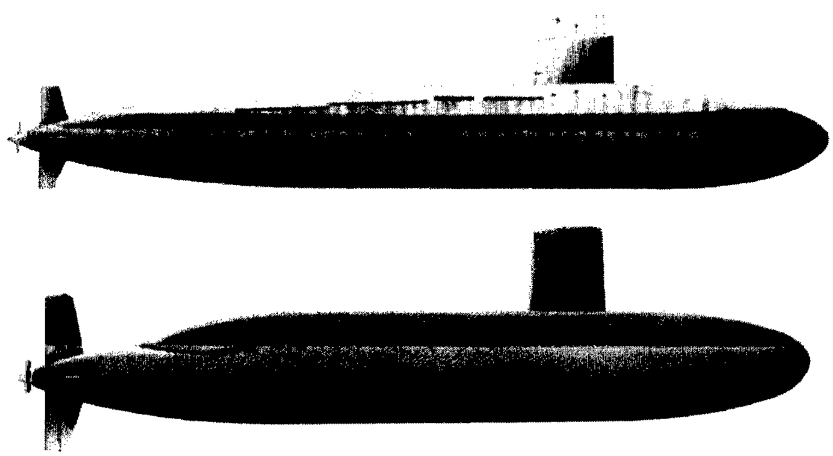


Figure 14. Profiles of Japanese submarines Yuushio (1979) and Harushio (1989) respectively [6].

In the author's opinion it would be difficult to improve on this shape but this opinion would need confirmation by proper measurements.

5.2 Skin Friction (Laminar flow - transition - turbulent flow - separation - roughness)

The skin friction drag on a flat plate parallel to the undisturbed flow may be laminar or turbulent or a mixture of both. Laminar flow consists of one layer of fluid sliding smoothly over another at a different velocity. The velocity changes from zero at the surface to the free-stream velocity over a very short distance normal (at right angles) to the surface. The laminar boundary layer has low friction, very low noise, occurs at low free-stream velocities and is rarely found at higher velocities in a given fluid (sea water in our case).

The physicists use a relation called Reynolds number which becomes the criteria for similarity between model and full-scale when two different forces determine the flow pattern, namely inertial force and viscous force. The ratio of these two forces reduces by algebraic manipulation to

$$\frac{\text{velocity} \times \text{density} \times \text{length}}{\text{viscosity}}$$

So at a given velocity what might give laminar flow near the beginning, becomes turbulent the further one goes along the plate, that is, as the length increases.

Reynolds number allows us to examine flow on a real submarine in seawater by testing a model in, for example, a wind tunnel. If the Reynolds numbers are the same in each situation then we have similarity in the results. The proviso is that the flow in the wind tunnel is not supersonic and the submarine is fully submerged with no free-surface effects and no cavitation.

At higher Reynolds numbers the sliding layers of fluid in the laminar boundary layer overturn and rotation occurs in lumps of fluid. This is very noisy and the skin friction is much greater due to energy consumed in the turbulence. We then have a turbulent boundary layer. The change from laminar to turbulent flow is called transition.

On a shaped body where the pressure varies according to the shape, a region of falling pressure in the direction of flow encourages longer laminar flow in the boundary layer. Conversely a region of rising pressure in the direction of flow makes it difficult for laminar flow to be maintained. Roughness and waviness of the surface also act against laminar flow and promote turbulence.

It is very difficult if not impossible to maintain laminar flow on large objects moving through fluids, like airships, ships and submarines. On some subsonic aircraft fitted with specially shaped wings, laminar flow can exist with beneficial decreases in the aerodynamic drag giving higher speeds, greater range and better fuel economy. If only laminar flow could be maintained over a significant portion of the surface of a submarine then the benefits would be significant not only to speed, range and fuel economy but also

to noise reduction. [1]That is why so much effort is expended on researching boundary layer control, which the Russians claim to have demonstrated on the experimental submarine, BELUGA [9]. However there are equally large difficulties with all such proposals (see Section 6.5).

If the region of rising pressure in the direction of flow becomes too severe then this slows the fluid in the boundary layer; it may even bring it to rest and reverse the flow. Then the flow is no longer attached to the surface and is separated from it (of course some fluid is still in contact with the surface - there are no voids). This is called separation.

With a laminar boundary layer separation occurs more readily, whereas for a turbulent boundary layer the greater energy in the layers close to the surface allow them to penetrate much further into the region of rising pressure before they are brought to rest and the flow separates from the surface.

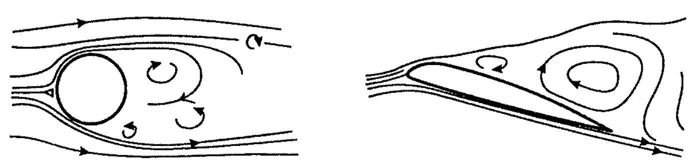


Figure 15. Examples of separated flows

In the separated region large, slow moving, noisy eddies are formed. The drag on the body increases dramatically. Examples of separated flows are shown in Figure 15.

[1] A laminar boundary layer creates a gentle hiss; a turbulent boundary layer creates a roar. However the boundary layer noise is confined and does not spread to the far field. It is termed pseudosound as the noise is contained locally. It can affect a contiguous sensor but decays as the inverse square of the distance. True sound such as created by a vibrating panel or the beats from a propeller blade (see later) decay as the inverse of the distance [46, pp. 254-258].

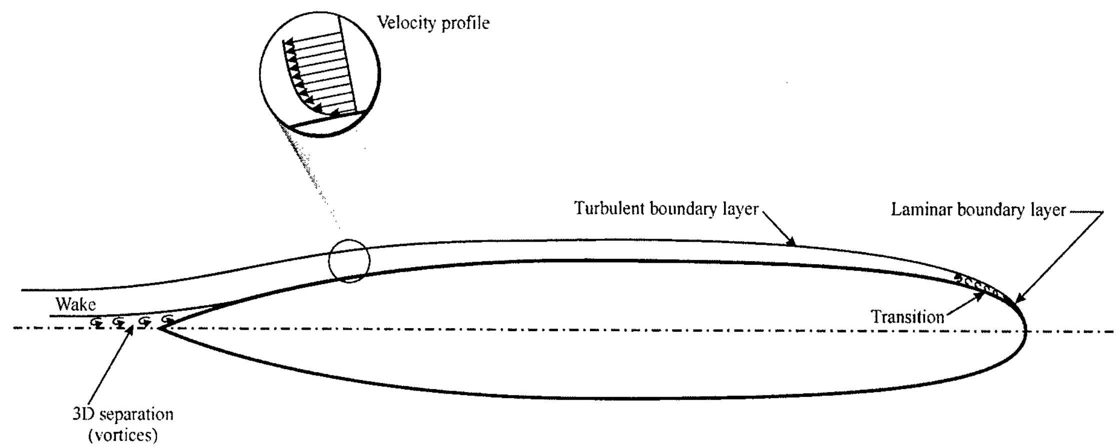


Figure 16. Flow around a submarine

Figure 16. illustrates the boundary layer growing as it extends around a submarine shape. Laminar flow may occur on the nose portion but will be turbulent thereafter. Note the increase in velocity in the boundary layer from zero at the surface to the local value of the freestream some distance from the surface (a short distance since boundary layers are relatively thin).

If the laminar boundary layer is formed on a blunt nosed submarine shape then a separation bubble may exist. Transition over the bubble can be followed by turbulent reattachment, which is rather noisy and should be avoided [25].

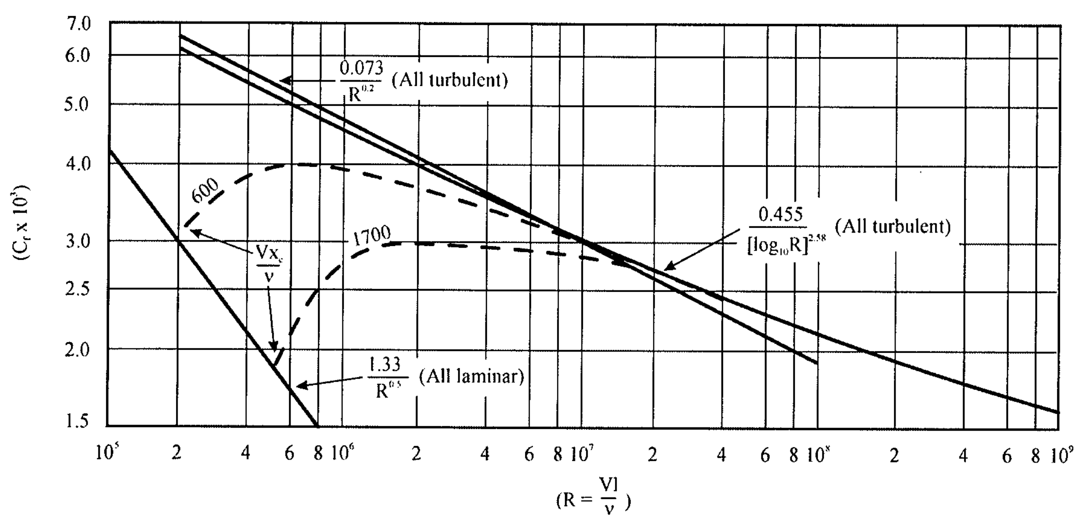


Figure 17. Friction drag coefficient Cf versus Reynolds number R for a flat plate parallel to the undisturbed flow.

Blunt noses have other significant effects, which will be discussed further on. To complete the section on skin friction we need to consider the effects of roughness. The graph showing the variation of skin friction with Reynolds number is shown in Figure 17.

The graph shows the all-laminar boundary layer, which only exists at low Reynolds numbers, whereas the turbulent boundary layer exists up to Reynolds numbers of 10^9 and beyond. Note the Reynolds number of Collins travelling at 5 knots in seawater is 1.6×10^8.

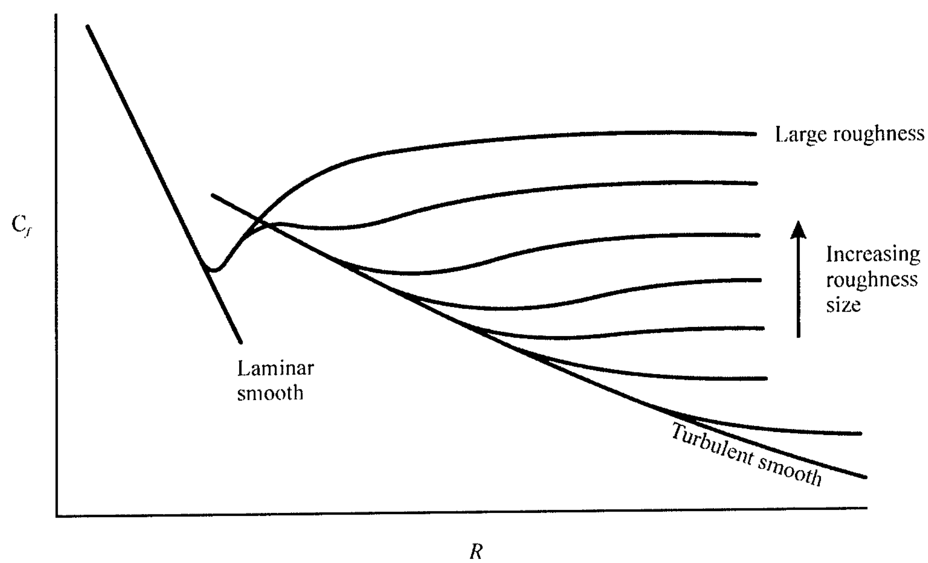


Figure 18. Sketch illustrating variation of friction drag of a plate at zero incidence with roughness height.

Different degrees of roughness raise the skin friction above that of a turbulent boundary layer on a smooth surface (Fig. 18). The subject is complicated since there are many variables.

Some types of roughness are independent of Reynolds number while other kinds are not. Roughness may occur because of the following:

- Structural roughness, waviness, welds, change of section
- Local damage
- Corrosion pitting
- Rust
- Paint failures
- Blisters
- Rough paint
- Fouling

The resistance increment will vary with type of roughness. The combination of the types of roughness will vary from ship to ship and during the course of a long patrol. Burcher and Rydill [1] suggest an allowance for fouling in temperate waters by an addition of 0.125% to the friction coefficient per day out of dock up to a limit of 180 days. Tropical waters cause more severe growth.

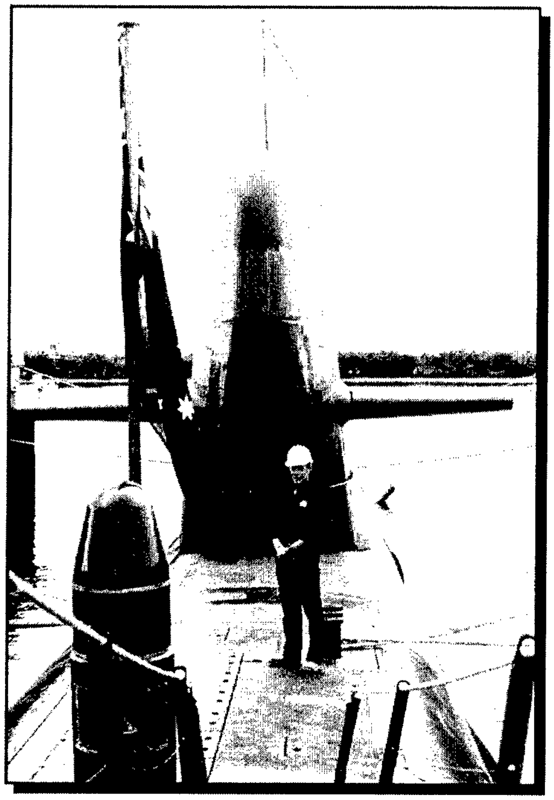
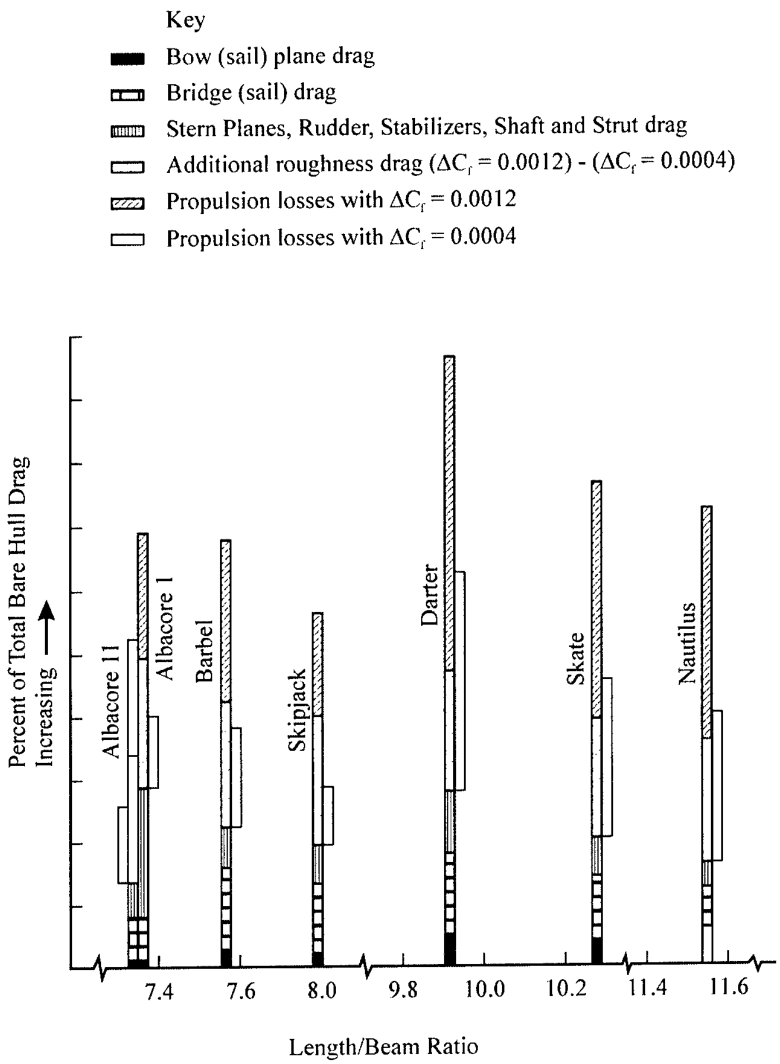


Figure 19. Shows rough nature of finish on foredeck.

The rough nature of construction of a submarine can be observed on the foredeck in Figure 19.

Captain Arentzen in [12, Fig. 8] reproduced here as Figure 20, shows the additional losses on various submarines. Roughness losses are a major contributor especially on the better-shaped boats.



Comparative appendage resistance, roughness drag, and propulsion losses for submarine forms of 100,000 cubic foot volume.

Figure 20. Comparative appendage resistance, roughness drag and propulsion losses (at constant volume)

5.3 Bluff Body Drag - Masts and Snorkel

On a bluff body, the boundary layer may exist on the fore part and the flow may separate thereafter. Hence the drag on the body is almost entirely pressure drag, high pressure in front and low pressure in the rear. To give an idea of the effect, the two bodies shown in Figure 21 have the same drag, one streamlined, the second a circular cylinder with its axis

normal to the flow. The results come from documented drag measurements and details can be found in the appendix.

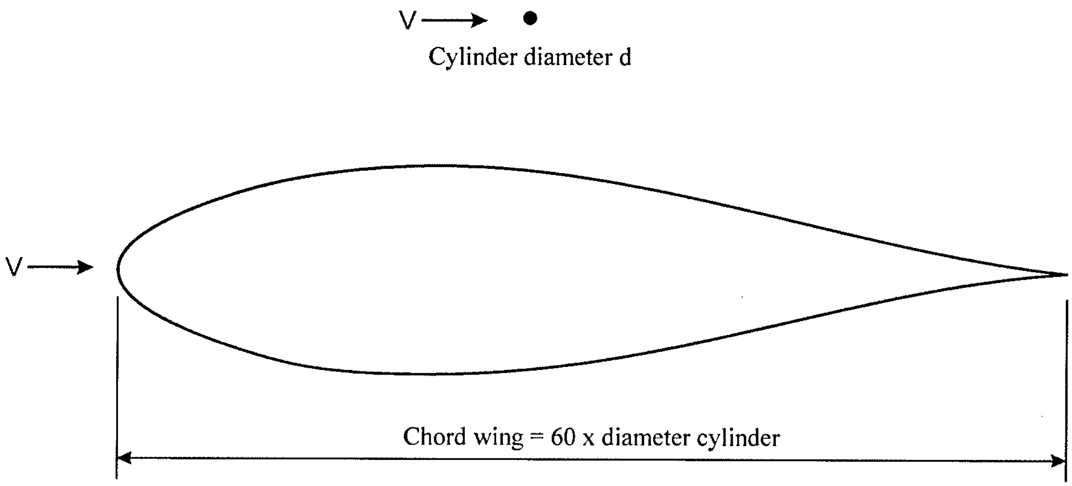


Figure 21. Drag of cylinder equals drag of streamlined shape

With various masts that may be raised it is possible there may be opportunities for reducing the drag.

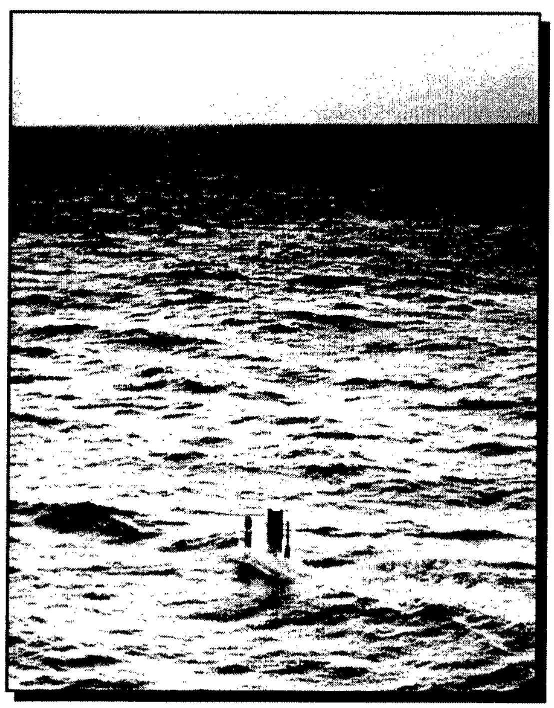


Figure 22. Masts raised when submerged

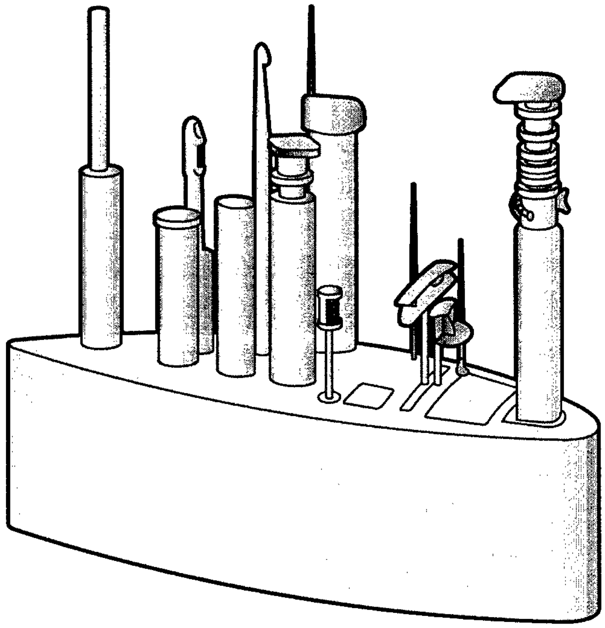


Figure 23. Drawing showing a submarine mast arrangement

Figure 22 shows masts raised while submerged and the drawing (Fig. 23) shows what may be raised on a submarine.

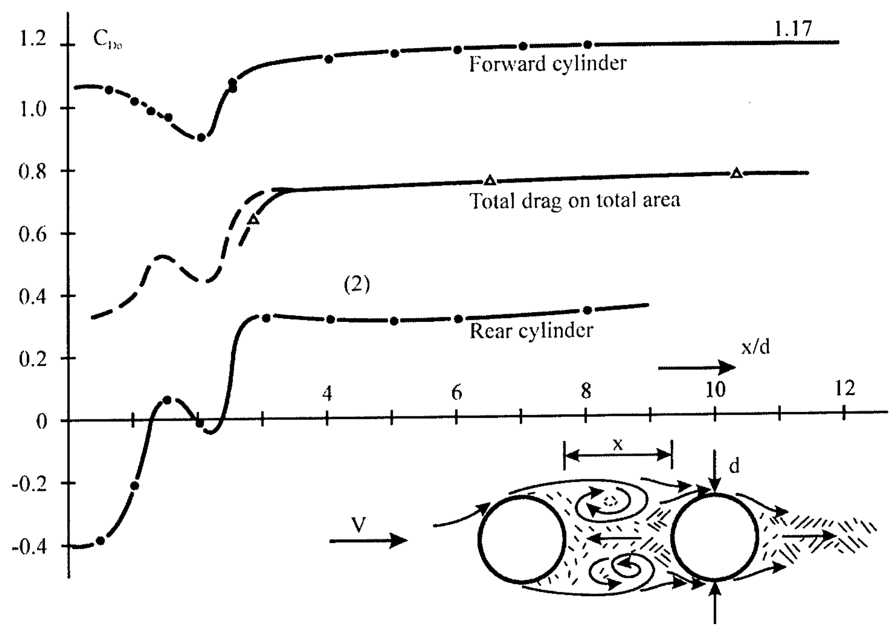
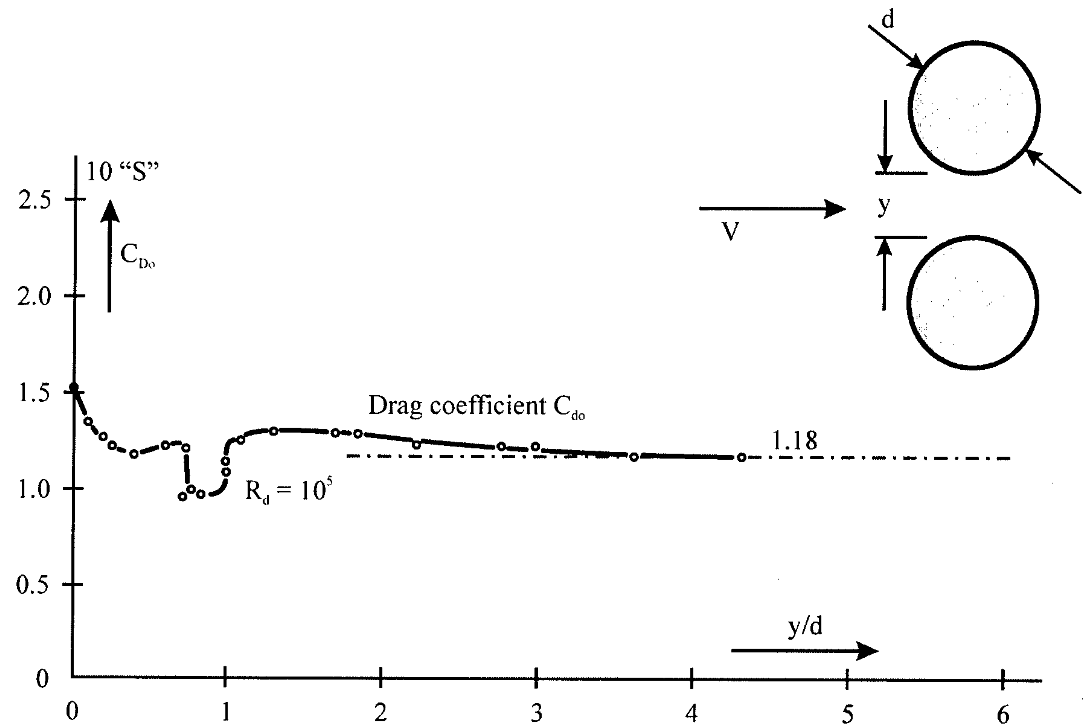


Figure 24. Drag coefficients of two circular cylinders, one placed behind the other.

Hoerner [26] shows that if cylinders are placed close one behind the other, the total drag is reduced significantly (Fig. 24).



Drag (2,a) of a pair of circular cylinders placed side by side

Figure 25. Drag coefficients of circular cylinders, side by side

Placing the cylinders side by side increases the total drag beyond that of two cylinders added separately (Fig. 25).

The fuel savings on a 9000 nautical mile voyage would be a positive incentive to reduce the drag. A snorkel tube of 700mm diameter and immersed length 3.2m requires over 90kW to thrust through the sea at 10 knots. A properly streamlined tube would require less than 5 kW. Further the near circular tube could well suffer from Vortex Street vibrations. Finally, the wave drag on the exposed tube (not included in the estimate) is not small and would add to the energy consumed.

The drag at 10 knots on a 300mm diameter search periscope, 3.2 metres in height, is six times greater than that on a streamlined shape of the same height but chord extended to three metres (see appendix). The power consumed at 10 knots is reduced from 40 kW for the periscope to 6.7 kW for the 3 m streamlined fairing. It should be possible to contain all masts and the snort within this streamlined shape. The drag on a number of masts is not

known but would be greater than that on one mast as there is some offset. (See Appendices for drag on masts and snorkels.)

The whole arrangement of masts and scopes should be properly studied and if possible streamlined so the drag can be minimised. While it may be possible to improve the arrangements of some of the masts, such as the viewing periscopes, which may no longer need to be pressure hull penetrating, the snorkel, with its need to provide large volumes of air, can hardly be reduced in cross-sectional size. But, it could be properly streamlined.

Any all-encasing streamlined fairing should not extend above the waterline where it might increase the chance of detection. Smaller streamlined extensions would be needed above the water.

5.4 Drag on Appendages

Appendages are objects that obtrude into the mainstream about the basic streamlined body and cause additional drag. A typical one is seen on Collins in the form of a long tube leading from the aft end of the casing (Fig. 26).

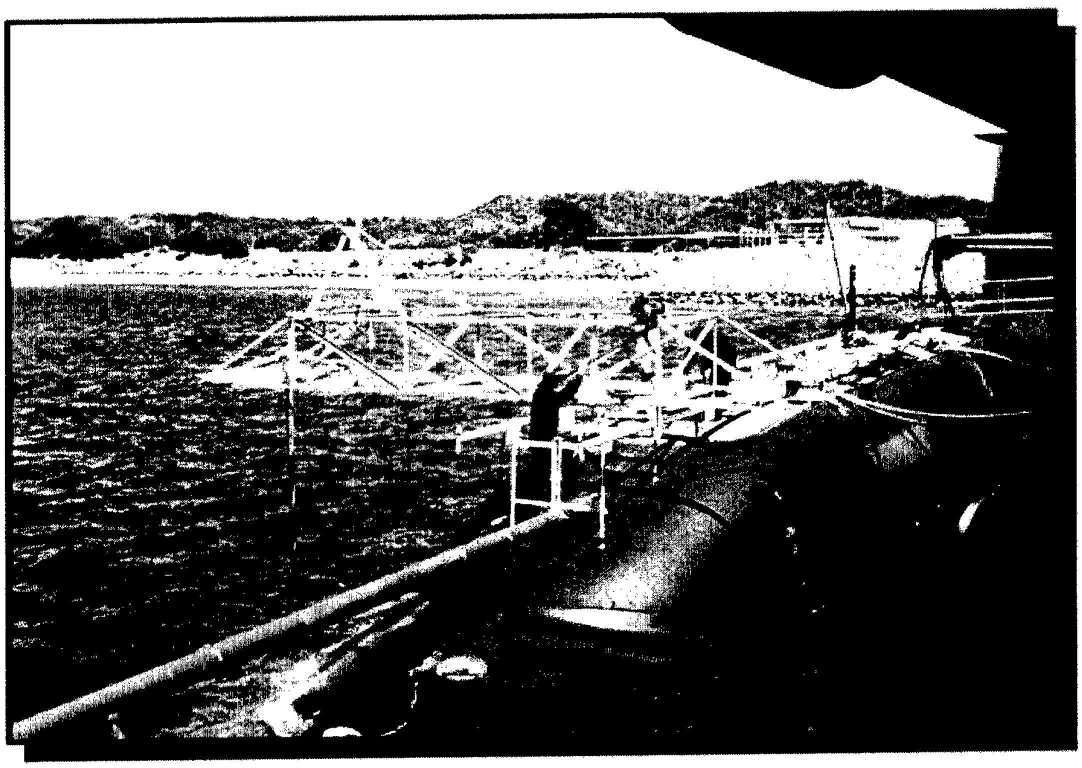


Figure 26. Fixed tube for towed array

This tube, of significant diameter, carries the towed array clear of the propeller and the two upper control blades. Two inclined struts support it towards its aft end. It is arranged with its major axis parallel to the centreline of the boat. The streamlined flow induced by the propeller and the contraction of the aft end of the hull, crosses the tube at an angle estimated as 20 degrees.

Hoerner [26, Fig. 18, pp. 3-11] shows the drag coefficient Cd=0.07 at 20 degrees inclination.

Hence the power losses at 10 knots submerged is 15 kW and this loss is continuous (See Appendices). An alternative arrangement of controlling the towed array could be devised. It is noted the Soviet Victor Class SSN has a large pod mounted above its vertical aft fin. American SSNs appear to stow a towed array in a long tube against the hull. With a fixed forward portion of an aft control fin it would be possible to lead a miniaturised towed cable within the natural shape of the fin and exit at the tip. A photograph of SSBN 619, Andrew Jackson, in dry dock shows the towed array exiting from the fixed tip of the starboard aft control fin [47, p. 202]. Seawolf has a fifth aft mounted fin but not moving, through which exits the towed array [47, p. 212].

5.5 Control Surfaces

Some appendages are necessary for control and cannot be eliminated with present technology. These are the forward hydroplanes needed for accurate depth keeping when slow and shallow at periscope depth. Bow mounting gives better control especially on the teardrop hulls where the bows tend to rise near the surface. They also provide more rapid diving. Extended, they are liable to be damaged and so are often retractable. Fin mounting creates less water and hydraulic noise near the bow sonar but not such good control. Their internal operation requires the fin to be larger [14, p. 35].

The aft control surfaces may be either X or cruciform. Mounting forward of the propeller produces a noise-producing wake from each control surface, affecting smooth propeller behaviour. Arrangements for the control surfaces aft of the propeller are awkward and were abandoned on Albacore after modifications. Oberon with twin screws had such an arrangement, as did the earlier (1971) German Type 206. They have not been seen since.

Captain Jackson, US submarine designer, [4, Fig. 7] showed the smaller turning circle achieved by X-form control surfaces on Albacore compared to the original conventional arrangement. Cruciform arrangements give control techniques easily understood by human operators. However, as with modern aircraft, computer control reduces the chances of catastrophic human error, so X arrangements then appear advantageous.

Some control surfaces are all moving and mounted flush with the skin as on Collins. Some have a part fixed together with a moveable control section behind. Some of these latter arrangements have a forward horn to reduce control forces [28, p.178].

Some of the fully moving fins have a fixed portion inboard as on the forward fins of British Valiant [28, p.172] and what appears as a non-moving cuff on the Dutch Zeeleeuw [28, p.180].

It is the opinion of the author that aft mounted control fins when fully movable, because they are operating in a thick boundary layer at the aft end of the submarine, would suffer boundary layer separations on the low pressure side of the fin when it is angled for course corrections. These separations would cause unwanted noise and drag. If this is the case, then a non-moving cuff would take better care of the flow problems at the fin-hull intersections.

A disadvantage for the fully moving sail-mounted forward fins comes from the loading on the shaft and bearings (Fig. 27) that have to operate when under full hydrodynamic bending loads. To absorb these very high bending loads in the encased mounting requires both large diameter shafts and wide spacing between the double bearings. This mitigates against any desire to narrow the width of the sail, an example of the consequences of a design decision.

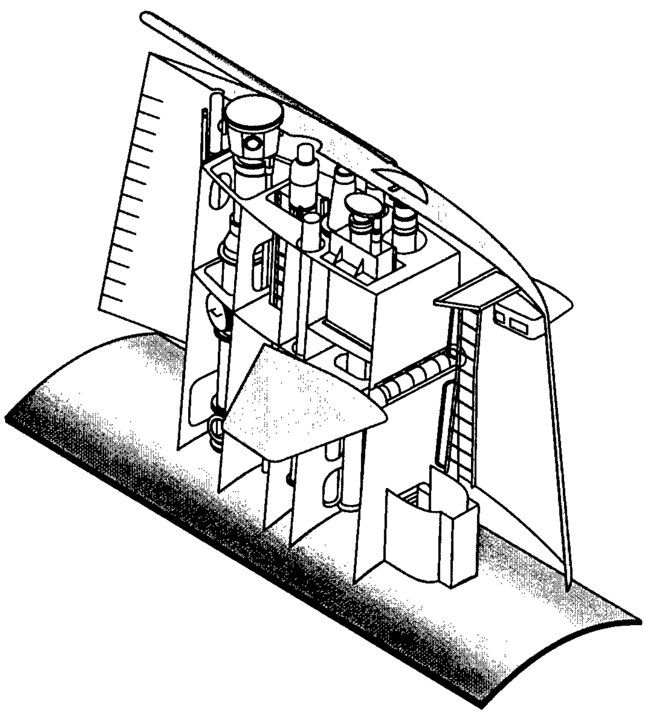


Figure 27. Shaft connecting sail mounted hydroplanes [46]

Alternatively, the forward fin could have a fixed forward portion, the transverse beam (spar) carrying the bending loads could extend through the sail, therefore carrying the bending loads in an efficient manner, the sail could then be narrower, the sail drag would be smaller and the diving control would occur through the adjustable portions hinged aft of the main spar. This arrangement appears to have been adopted on the Permit boat as

shown in Miller and Jordan [28, p.142]. Forcing a surfacing submarine through an ice cap would not be an Australian reason for having fully moving sail mounted forward fins [7, p.184].

Any changes in control surface arrangement need to be studied by CFD and wind tunnel tests to check the effects on turning circles and dynamics and control.

5.6 Sail

The major appendage is the fin (sail, conning tower, bridge, fairwater), which is a large contributor to the overall drag, as shown in Figure 18. Friedman [7, p.140] comments that a large sail may contribute up to 30% of total resistance and a fully appended hull may have between 20 to even 60 % more resistance than a bare hull as with the Type VIIC.

Miller and Jordan [28, p.142] in discussing the Permit Class refer to the small sail, which contributed only 8-10% of the total resistance. However this led to other problems and is an example of the conflict in design. The small size of the sail restricted the number of sensor masts for proper operational functioning; the required number could not be accommodated. The later Los Angeles Class, with double the power (30,000 hp), had a larger fin (with larger drag) carrying all the necessary masts.

The sail has a number of important functions, it provides:

- stowage and support for the masts when raised,
- a conning position when in harbour for berthing,
- safe transfer to the open deck at sea without swamping,
- underwater handling stability, and
- an ability to operate covertly while submerged at shallow depth.

Admiral Hervey [14, p. 32] discusses these requirements and says, "There is a balance in choosing sufficient sail height. If it is too short there won't be enough support for the masts or the boat speed will be restricted with raised masts. It is desirable to keep the submarine as deep as possible while using the periscope especially in bad weather. On the other hand if the sail is too tall the snap roll can be excessive. A non-hull penetrating periscope is a major requirement." This would allow the sail to be positioned on criteria other than what is best for the periscope. Reducing the drag of all these masts after the principle demonstrated in Figure 19. might be worth exploring. It might be possible, with careful hydrodynamic design and understanding of the physics, to increase snorkelling speed thus shortening transit time.

Sails on US submarines tend to be like streamlined stub wings, while many Russian designs favour longer squatter shapes. An announcement from Naval Surface Warfare Center, Carderock Division [29] shows an experimental sail more like some of the Russian shapes that are reported to have additional volume (factor of four) with some expected degradation in hydrodynamic and acoustic characteristics. The vertical shift in the centre of gravity due to the sail is considered by Abkowitz [12, pp. 686-7] to give rise to the snap

roll induced in a turn at speed. Before reading Abkowitz the author considered the snap roll was caused by the sail running at an angle of incidence to the curved flow in a turn, thus producing a large hydrodynamic force in the sail acting radially inward [1]. The sail also acts as an obstruction to the vortices from the cross-flow over the hull in a turn. This in turn gives uneven pressure distribution between the top half and the lower half of the body. The nose may rise and the stern may dip depending on the geometry [1].

The size of the sail and the amount of liquid it would contain at the moment of surfacing can give a transitory but dangerous effect on the vessel's stability (Fig. 28).

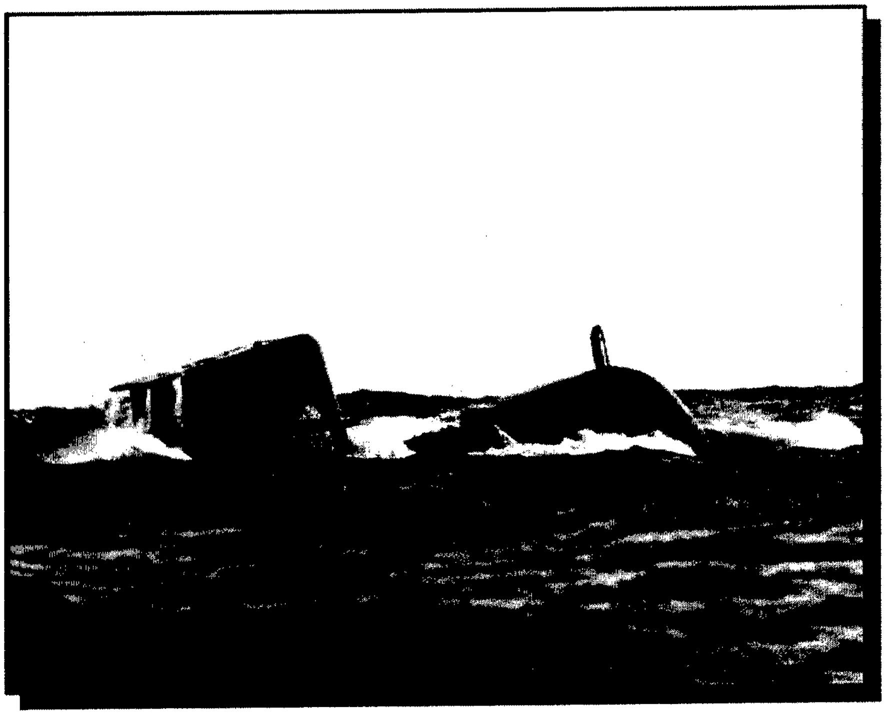


Figure 28. Submarine surfacing

The sail plays an important part in the dynamic stability of the vessel. Where it has been located in the past has been determined to a large extent by the needs of the hull-penetrating periscope. If this requirement is altered through changed technology for the periscope then the sail can be repositioned. The problems of stability and control will be discussed later.

The drag on the sail is composed of pressure drag, skin friction drag and interference drag, which originates at the join of the sail to the top of the main body. The interference drag is common to all appendages joined to the main body or, for example, to the forward fins when they join the sail. When operating at an angle of incidence as in a turn, further drag is created by the tip vortex and is called induced drag.

Richard Von Mises [31] remarks, "If to a well streamlined body, some appendage is added, the resultant drag is larger than the sum of the two drag forces that are found when each part is tested independently. The surplus depends on the location of the disturbing part and reaches its maximum when the location is aft of the maximum cross-section of the main body. The drag contribution due to the interference is on average 30% and in the worst position more than 50% of the separate drag of the additional body.

Skin friction is minimised by keeping the sail as small as possible. The skin must be as smooth as possible with no obtrusive edges, joins or holes. All masts should fit smoothly into the outer skin.

Pressure drag is minimised by a proper streamlined shape with maximum thickness about 45-50% of chord. Whether laminar flow can be achieved on the fore part of the sail is uncertain. The thickness-to-chord ratio should not be greater than 12.5%.

Figure 19 shows some of the surface on the leading portion of the sail on Collins. From viewing the photograph the only really acceptable portion is that above the windows. The forward facing holes and indentations are quite unacceptable from the point of proper flow. The handrail could be better shaped as with modern roof racks seen on cars.

Aerodynamic engineers have studied interference drag, such as that at the base of the sail where it joins the hull, for many years. Arising from the interaction of the upstream boundary layer as it approaches the vertical stagnation line on the leading edge of the sail, a horseshoe vortex is formed about the base of the sail. The stagnation line is formed by the flow dividing either side of the sail. The total pressure near the base on the stagnation line at the height of the boundary layer is greater than that below it. This initiates a flow downwards which ends up as a vortex wrapping about the vertical centreline of the sail.

The results of one piece of research into horseshoe (necklace) vortices suggest that thinner nose shapes (on the sail) would produce a smaller necklace vortex [30]. It is difficult to eliminate the horseshoe vortex by changing geometry, but more on this later.

Extra drag is created along the internal corner between the top of the hull and the side of the sail, which is where the angle between the two surfaces is less than 180 degrees. Contra-rotating vortices are formed along longitudinal corners as well as the skin friction increasing. The interaction of the two boundary layers, one on the body, the other on the appendage, can create higher pressure-drag on the appendage as suggested by Von Mises [31].

5.7 Flood Openings

Flood openings and holes in the hull and casing represent a measurable and unwanted source of noise and drag. The sail and casing can contain a large amount of water, which has an adverse effect on stability when surfacing until it drains. It is essential that it drain very quickly (Fig. 28).

The requirement for a World War I and II submersible to be able to submerge in seconds is no longer top priority (100 feet in 40 seconds for Type 21). To give some idea of the drag from flood openings, the first streamlined Type 21 could only achieve 15.7 knots submerged although model tests had predicted 18 knots. Decreasing the area of the openings increased the speed but also the diving time. The answer to both requirements may well be in articulated shutters [1, p. 109].

Holes are a source of noise as well as drag. Burcher and Rydill remark that special attention has to be paid to the shaping and alignment of these openings to avoid additional drag. Induced fluctuations of flow in and out of the hole due to variations of the stagnation point on the edge of the hole facing upstream cause fluctuating eddies as is arranged deliberately on a flute or organ pipe. Resonance can then accentuate the problem. While shutters may prevent this, their mechanical complication gives rise to other problems.

A higher drag but less costly and complicated solution is to arrange venetian grills which present an acute angle to the oncoming flow but allow a large area for crossflow of water to/from the internal volumes.

5.8 Extra Drag from Non-Smooth Cross-Sectional Shapes

Since 1996 the author has been studying the flow along a chine or what might be called an external corner (see [32]).

If a chine is carefully aligned with the flow, a pair of contra-rotating vortices is formed and the skin friction is increased near the corner. If the chine is not properly aligned with the flow then only one vortex is formed on that side of the chine where the pressure is lower. A crossflow is generated, which combined with the main flow, ends up as a longitudinal vortex.

It is not necessary to have a sharp edged chine in order to generate these mal flows. The original aft end of the casing on Collins produced major crossflows and vortices, which led to major undesirable effects.

Von Mises [31] describes the results of the drag on two ideal streamlined bodies, one of circular cross-section and the second of square cross-section. The second body is composed of four chines. The cross-sectional area of the two models is the same. The drag coefficient for the round cross-section was 0.045 and for the square cross-section 0.055, which is over 20% greater.

It is therefore necessary to make the cross-sectional shapes along the hull as smooth as possible, even with the added shape of a casing and to check the transverse pressure distributions which can generate the crossflows and associated vortices. It is noted that

some British submarines have casings with no internal corners [7, p. 92; 29, pp. 100-101]. The benefit in reduction of acoustic signature may be more important.

5.9 Nose Shape

The shape of the nose is most important, as it is associated with the positioning of acoustic sensors and torpedo tubes as well as the starting conditions for the flow around the hull. One solution is to place both major items one above the other and wrap a shape about them as a cover. This may lead to some unfortunate consequences.

The American submarines, almost entirely, have ellipsoidal nose shapes with the large passive sonar placed in the nose and torpedo tubes some way aft angling outwards from the surface at about 15°. Some British submarines have followed a mixed solution with the upper half of the nose shaped quite differently from the lower half and some rather harsh angles in the profile not exactly conducive to the best flow conditions (see Fig. 29). The bow sonar array on this boat was located in the lower "chin" and the torpedo tubes were moved further aft as in American designs. Updated vessels (Trafalgar Class) again appear to have nose profiles that are not conducive to smooth boundary layer flow.

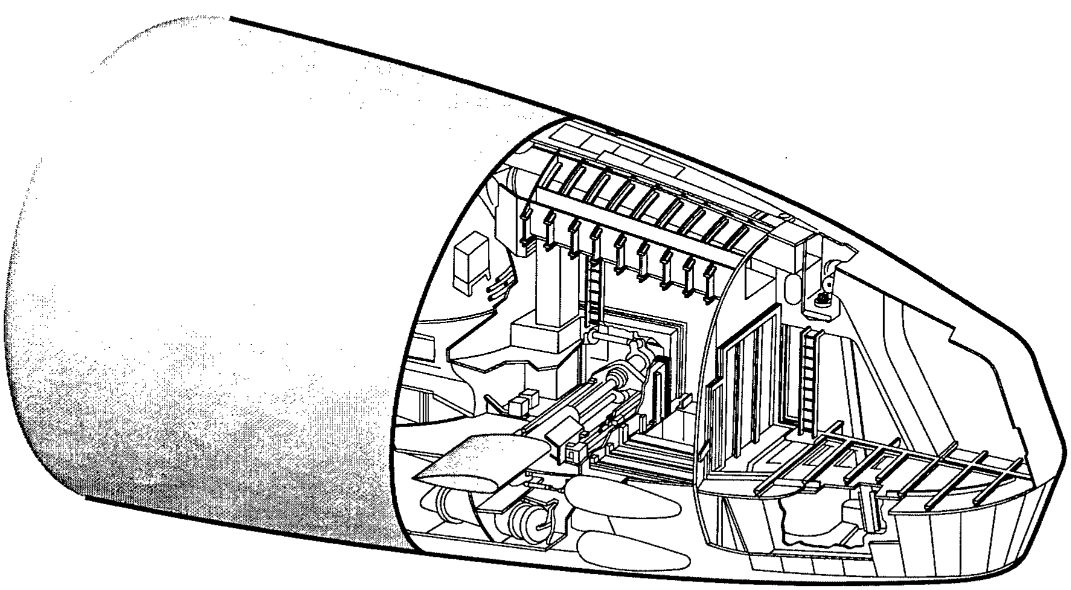


Figure 29. Cutaway drawing HMS Swiftsure [7]

Burcher and Rydill [1] discuss the importance of the bow sonar and how the effectiveness of operations of the vessel depends so much on the capabilities of its detectors. This is an area of conflict in design, as allowing the bow angle to be so distorted in order to accommodate the best detector together with the torpedo tubes, may result in such turbulent flows as to render the sonar ineffective.

The solution adopted by American designers with the passive sonar located in an isolated point well ahead of all other items appears as the better solution. Figure 30. shows the position of the bow sonar on the US Los Angeles. It is located more than 40 feet from the forward bulkhead [14, p. 32].

The Swedish solution was studied at their maritime research institute in Gothenburg and a paper presented at the 1983 symposium on naval submarines [33]. The authors begin by saying, "In order to achieve higher speeds and lower noise levels a more careful design of the hull form is required which leads to a more slender shape of the forebody." Further on they say, "...the resistance may increase substantially if a hydroplane dome is not properly integrated in the forebody." They continued talking about laminar flow, transition and turbulence and the disturbances to the flow caused by torpedo tube hatches as though there is no other position but the nose for the weapons. An argument for the blunt nose based on costs of production is also put and they say that both the resistance and noise level increase with the number of torpedo tubes. They then discuss how a low pressure peak which occurs just aft of the forebody will indicate the presence of a submarine to a mine.

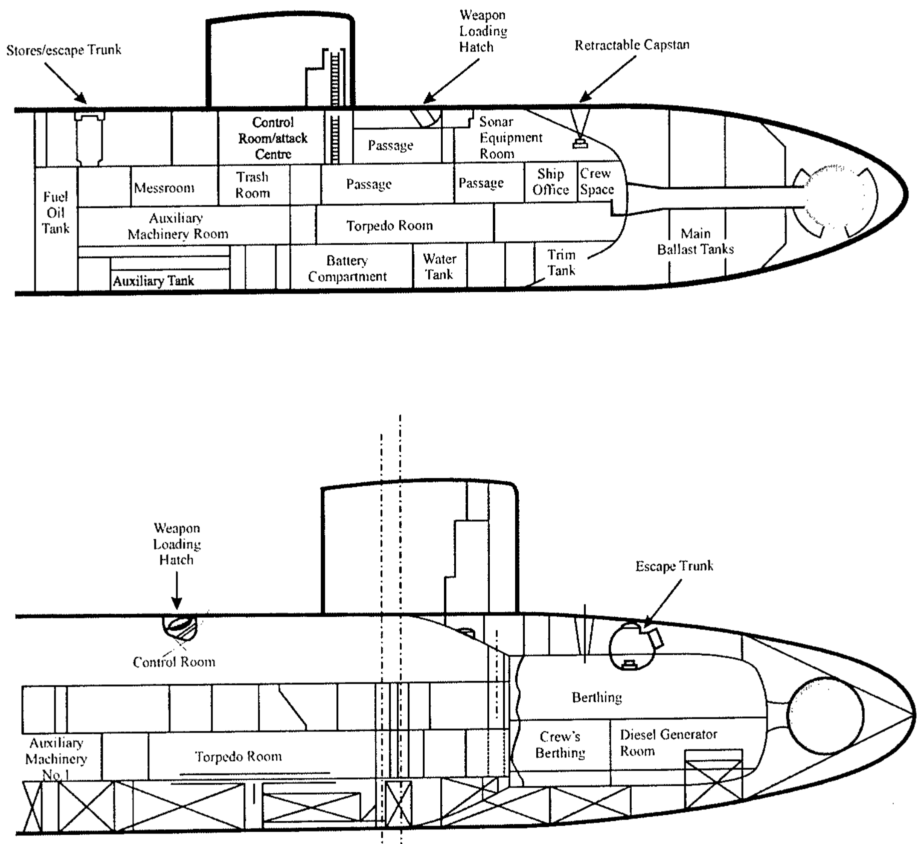


Figure 30. Bow sonars on US Los Angeles and US Sturgeon showing nose-shape and torpedo tubes.

The pressure distributions on various blunt nose bodies are then studied and for a forebody with an integrated hydrophone (see Fig. 9. in [33], repeated here as Fig. 31), the pressure coefficient over the top of the hydrophone reduces to an extraordinary low value of -0.95. Tests in their cavitation tunnel demonstrate that this low pressure can cause cavitation over the hydrophone.

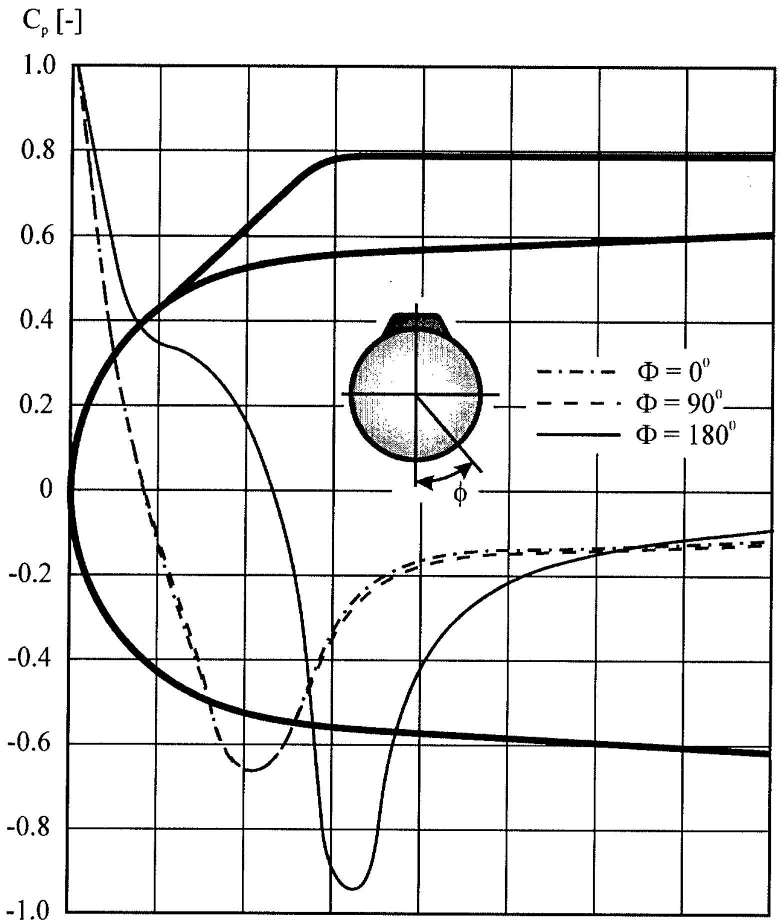


Figure 31. Pressure distributions on a forebody with an integrated hydrophone [33].

In the author's opinion their paper demonstrates the ineffectiveness of the design choice, blunt nose, large number of torpedo tubes and contiguous sonar above. Yet they state, "It is important that the hull design leads to low and uniformly distributed velocities along and in the vicinity of the hydrophone window. Further the local velocity should be a strictly monotonic function with a value increasing up to and abaft the hydrophone." It is important to point out that by Bernoulli's equation, low peak pressures are associated with very high local velocities not to mention possible cavitation. In this light, the Swedish arguments are contradictory.

A second Swedish paper from the same research establishment in Gothenberg in 1988 on Hydrodynamic aspects in Submarine Design was presented by Mr. Sten Hellstrom [25]. He states,

"It is vital to have the perfect flow around the submarine or at least know the drawbacks of a water flow that is disturbed in some way - by curved hull areas, sharp bends, knuckles, torpedo tube hatches, hand and foot supports, drainage openings and so on." He concluded by saying, "Building costs demand a short full submarine and as the required propulsive power follows the magnitude of the wetted surface and only to some extent the fullness, a full form with small wetted area will still have low resistance. The full form will also have a higher mean wake and hence a higher propulsive efficiency. A short submarine is also more manoeuvrable.

However, increasing the fullness is risky as we approach the limits in all respects.

- Full forebody with risk of separation, unfavourable pressure distribution and transitions at vital areas.
- Full afterbody close to flow separation and more sensitive to flow disturbances from appendages, deck and keel endings necessitating extreme propeller designs
- Short hulls close to instability with high requests on manual steering and autopilot"

These comments from two prominent researchers from a recognised research establishment do not appear to be logical. They point out how important the flow needs to be arranged over the nose; they show by experiment how a negative Cp of -0.95 can occur over the sonar on a Collins shaped nose (Fig. 31); they then say it is important to keep down building costs and presumably have a nose, which prevents the functioning of the submarine's most important device, its bow sonar.

In April 1990, a third article prepared by the same Swedish research establishment SSPA, appeared in the journal of Maritime Defence [34]. Arguments for lower building costs are no longer mentioned. Some of the same sentences from previous papers are included e.g. "It is vital to ensure an almost perfect flow around the submarine...".

Again they say,

"An important aspect of the forebody design is the acoustic performance. Two phenomena of particular interest are local laminar separation and transition between laminar and turbulent flow. The separation generates a noise of relatively high amplitude level that may cause severe disturbances to the hydrophones as well as radiation from the submarine. The position of the transition is important, since it affects the integrated acoustic energy over sonar windows. Both phenomena can be studied by numerical simulation of the flow.

An acoustic window is best located within a laminar region of the flow, since the self-generated noise of a boundary layer is lower than that of a turbulent one. In practise, however, this turns out to be difficult to achieve, in particular when considering a wide range of speeds. The worst situation is to have transition located near the upstream side of the window, since the integrated acoustic energy will then be higher due to the contribution from the turbulent boundary layer and the transition itself. Substantial improvements have been achieved by modifying the forebody in such a way that the transition is moved downstream to reduce the total acoustic energy by an increasing proportion of the laminar boundary layer."

R.J.Daniel from Vickers, at the 1988 Naval Submarine Symposium in London [35] said, "To provide the best sonar performance, that is to ensure that one detects the enemy before one is self detected, it is necessary to have the best sonar performance while making the least possible noise. The form must be streamlined to reduce the generation of eddies and hydrodynamic noise. Particular attention must be given to the bow form and to the elimination of vortex generators in the vicinity of the sonar."

Hoerner [26, pp. 3-12] shows that the drag coefficient for an ellipsoidal nose is -0.05 and for a hemispherical one 0.01, both very low but the coefficient for the ellipsoid is 1/6th that of the hemisphere.

5.10 Torpedo Tubes

Burcher and Rydill [1] discuss the siting of torpedo tubes. They first consider the undesirable interactions between firing a torpedo and the operation of the sonar. They discuss the alternatives of sonar above or sonar under the tubes, loading problems, ballasting after firing to preserve trim and then shutters for preserving surface continuity. They do discuss angled discharge from positions aft of the nose and the problems of such locations, namely, the angled tube arrangement occupies far more space, they claim, because to load the tubes, torpedos have to be aligned across the compartment or downward through the decks in order to get them into the tube.

Then they comment that a hydrodynamic problem can arise because a weapon being discharged at an angle to the flow from the side of the hull can experience a greater toppling moment causing damage to the torpedo as it leaves the tube. They then say toppling is less of a problem at the bow as the torpedos are being discharged into an area close to the stagnation point where there is a small cross flow at the tube opening. While there are some designs with a few of their tubes so located, near the stagnation point, (e.g. German TR 1700) once a tube is located some distance from the stagnation point on a bluff nose then the cross flow is far greater than the 15 degree cross flow on a torpedo exiting from a tube located further aft. This follows from the streamlined flow around a nose and as one example the flow field about a hemisphere is shown in Figure 32. This shows that torpedos fired from a nose like Collins would exit in a cross flow much greater than 15 degrees for those four tubes outboard of the two more centrally positioned. Moreover the velocity there would be higher than the vessel's forward velocity.

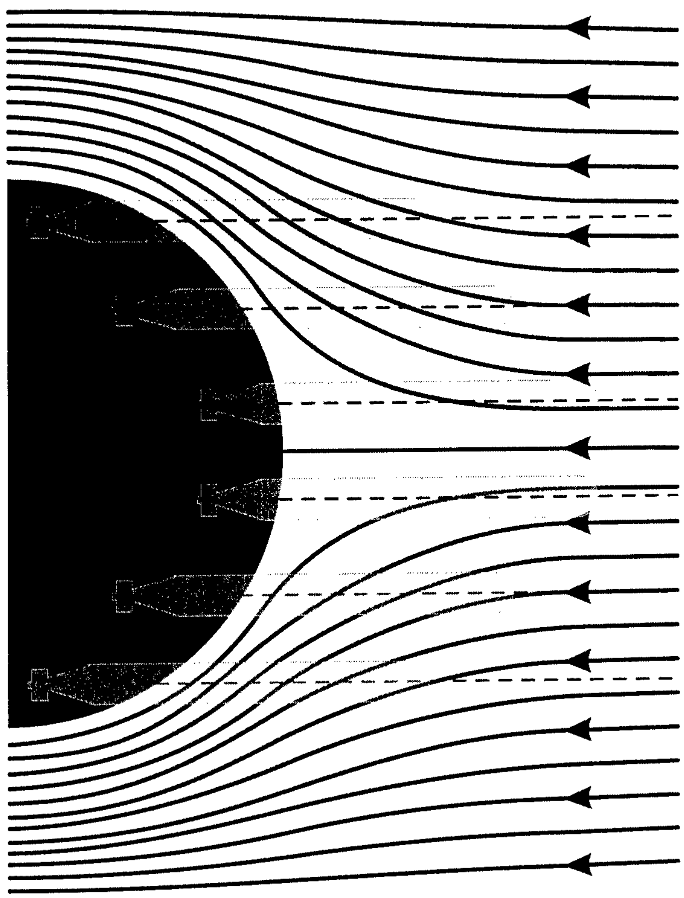


Figure 32. Bow streamlines on a hemisphere. Dashed lines of torpedo tubes.

All the papers and books studied in this survey confirm that the flow over the principle sonar device should be as smooth and quiet as possible. If not laminar flow, which is the quietest, then transition should be avoided and any surface irregularity such as a torpedo tube shutter should be placed elsewhere. Vortex generators, as on a retrousse nose, should be avoided. It appears that an ellipsoidal shaped nose with smooth and gentle pressure variations along streamlines, containing the principle sonar and the angled torpedo tubes arranged further aft is about the best compromise.

Current torpedos guided by wire may exit in different directions and be guided to their targets so there is no current reason for pointing at an intercept on a target. Even with the 15 degree angled exit on tubes positioned aft of the nose, it would still be possible to aim with any future non-steerable weapon. In 1957, the US Navy fired angled torpedoes at up to 20knots safely from an oiler Neosko [47, p.136].

5.11 Side Arrays

The requirement for longer range and lower frequency sonars has led to the development of distributed arrays which demand length and depth in such a way that a major portion of the submarine hull has to serve as a platform for the flank array. This is one reason for the greater length of parallel section in the hull despite the hydrodynamic requirement for a changing section. However this requirement may no longer be valid. Often these arrays are mounted proud of the surface of the hull (or casing) which creates not only extra drag but are so shaped as to create a lot of interfering turbulent noise with the result they cannot function properly (see Fig. 33). Their design and arrangement leave a lot of room for improvement.

Seawolf mounts side arrays on the hull (rather than the casing) and below the maximum beam [47, pp. 212, 215].

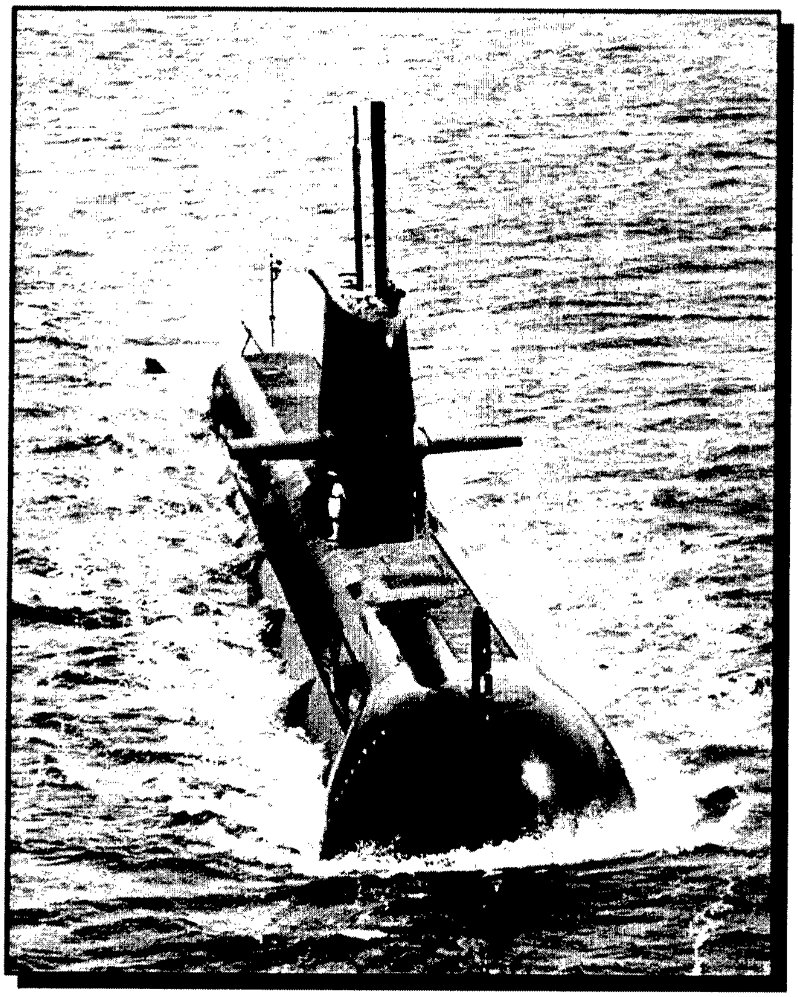


Figure 33. Shows side arrays projecting into the flow.

5.12 Shape of Afterbody and Propeller Interaction

The best aft shape giving the minimum drag for a streamlined body being towed through the fluid may be different from one being thrust through the fluid by an aft mounted propeller. This is because the inflow (increase in velocity) induced by the propeller affects the pressure distribution on the body.

Further, the efficiency of the propeller depends on a number of independent variables that need to be understood. The thrust is achieved by imparting increased momentum to the fluid passing through the propeller disc. A given thrust can be created by a small diameter jet of high velocity or by a larger diameter jet at a lower velocity.

The efficiency of propulsion depends on the final jet velocity well downstream of the propeller relative to the velocity of the vessel i.e. the lower this relative velocity the higher the propulsive efficiency. In other words, the jet velocity represents lost energy. Therefore it is more efficient to give lower acceleration to a larger amount of fluid.

There are two important and opposing factors in the physics. Of the fluid entering the single propeller disc on a submarine, much of it is slower moving fluid due to the boundary layer on the body of the submarine. This slower moving fluid is accelerated through the propeller to give the required thrust but does not reach the same velocity downstream as the jet of a propeller operating outside the boundary layer, which is accelerated from an initially higher velocity. Therefore the propulsive efficiency of the single propeller of a submarine is more efficient than say two offset propellers on the same submarine at the same velocity (same thrust) that are located outside the boundary layer.

Consequently on a fuller stern where the drag of the stern alone may be higher than for a finer stern the improved propulsive efficiency can, with careful adjustment, more than compensate resulting in lower fuel consumption.

The second factor arises from the acceleration of the fluid into the propeller. This gives a higher velocity over the afterbody and hence more skin friction drag. Rather than call this change an increase in resistance, propeller analysts refer to it as a thrust deduction.

A further advantage of a fuller stern is that it provides buoyancy in a location where there are often heavy weights of machinery such as a large electric motor.

Once again the design is a result of a number of interacting factors all of which need to be carefully considered.

5.13 Propulsors

Some remarks on the general principles of propulsors have been included in the previous section dealing with propeller interaction. It is not the intention in this section to deal with propeller design or that of a shrouded propeller with perhaps some fixed blading. This is a vast subject and would require a book to describe properly. Nevertheless, there are some further main points to be mentioned.

5.13.1 Wake Variation

Due to upstream appendages the wake field entering the propeller disc is not uniform. There are shadows cast from the sail and the aft control surfaces. In some cases a badly faired casing can leave not only velocity decrements but also large vortices that enter the propeller disc. These shadows can create a momentary increase in the lift coefficient on the blade in the shadow. The lift coefficient can double due to the momentary change in the angle of incidence. This causes beats. The propeller is a major source of low frequency noise emanating from a submarine.

5.13.2 Shrouded Propeller

This problem of noise, so critical for a submarine, can be alleviated by a more complicated, heavier and much more expensive arrangement, a shrouded propeller. If a shroud is to be used then it has to be supported and a set of fixed pre-rotator blades are arranged to provide a pre-swirl in the opposite direction to the rotation of the propeller. This then has the advantage of leaving less swirl in the flow behind the set of rotating blades. All post swirl in the flow represents lost energy. To overcome this, another set of fixed blades can be provided which leave only the desired axial flow in the final jet.

The latest British SSNs have been fitted with these multi-bladed ducted propellers. It is understood they have also been fitted to some American submarines. Burcher and Rydill [1] discuss some of the above matters (see Fig. 34)

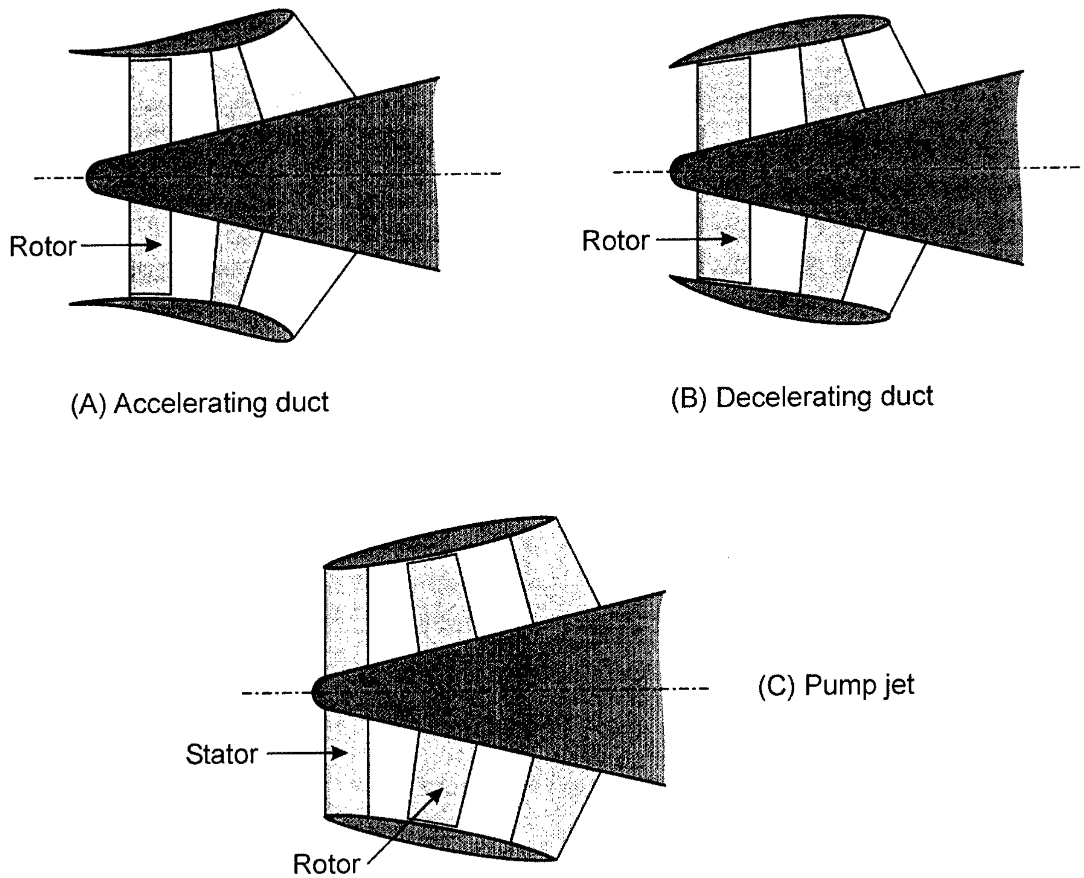


Figure 34. Types of ducted propulsors

6. Application of Hydrodynamics to a Future Design

6.1 Introduction

Having outlined most of the major features of hydrodynamics, which could apply to a future submarine design, the question is how does one then apply these? How does one check there are no undesirable features? How can the performance be predicted? How can the drag be reduced?

The tools at the disposal of the designer, although in different form, have been available since the time of William Froude but now augmented by computational fluid dynamics, wind tunnels and water tunnels. Not that a submarine needs to be tested submerged in a towing tank, but model testing is a major aid in the art of prediction. I say art because there are some important areas where experience helps in the prediction such as the effects of roughness.

Computational fluid dynamics (CFD) is a developing tool, which is quicker and perhaps cheaper than model testing, but has areas where the predictions are doubtful. The two together, CFD and model testing, give greater confidence in the predictions.

6.2 Parametrics

Captain Harry Jackson presented a paper on submarine parametrics to the 1983 International Symposium on Naval Submarines. By detailing the hull parameters he arrives at a displacement and a wetted surface. This proceeds to an effective horsepower required for the bare hull in terms of the skin friction and form drag with an added allowance for the roughness and drag due to vent holes and fouling. He then adds the sail drag (found from submerged towing tank tests), drag from control surfaces and any other significant items, to estimate the total submarine resistance.

The next major variable in the equation is the propulsive efficiency, which again is based mainly on past experience. Finally, curves can be drawn which show submarine velocity against installed power.

This would appear a most valuable technique, which needs to be developed and proven for any future design. There is already a model available that can be used in a high Reynolds number wind tunnel to measure all the components of resistance and predictions can then be made on performance. It would be an advantage to complete the prediction by model testing the propeller first by itself and then installed on a model in the Tom Fink Cavitation water tunnel. This would establish the propulsive efficiency and wake fraction. These predictions can then be compared with actual field measurements of performance of the available full-scale submarines. Differences can then be examined and understood so that future predictions on a different vessel can be more accurate. At the same time CFD predictions can be compared and the knowledge base improved.

6.3 Wind and Water Tunnels

A paper describing the use of wind tunnels, water tunnels and towing tanks for testing models of submarines was described at the 1991 International symposium on Naval Submarines by three Canadian authors Watt, Tanguay and Cooper. They stated, "as the present Canadian submarine fleet was due for replacement the Defence Research Establishment had been developing their capabilities for examining submarine characteristics". Further, they stated when examining extreme and emergency conditions such as sharp turns and plane jams during depth changes that the hydrodynamics were complicated, non-linear, were not amenable to prediction by analysis or even sophisticated CFD. They stated, "To investigate these phenomena properly it is necessary to develop scale model testing capabilities".

Free surface and dynamic testing needs to be carried out in a towing tank and water tunnel. Dynamic testing, although possible in a wind tunnel, has the impossible difficulty of the added mass that is not present in a water tunnel.

The paper then discusses alternative support systems for mounting the model in a wind tunnel and the problems of propulsive tests, which are better done in a water tunnel.

In conclusion, the wind tunnel provided all the required information on manoeuvring characteristics and as well flow visualisation and flow field velocity measurements. It is noted that the DSTO wind tunnel used in the tests of Collins, while not as large as the Canadian tunnel, operates at a much higher velocity so it has a reasonable Reynolds number capability.

The large low speed water tunnel at Bell Bay, Tasmania has been used for dynamic testing but needs to reduce its level of turbulence. The Tom Fink Cavitation tunnel in Launceston is operational and can certainly be used for propulsive tests as well as for drag and flow studies.

6.4 CFD

Local CFD experience is constantly being developed. It is used extensively in the field of aerodynamics and to a lesser extent in hydrodynamics but all the principles apply equally. I have been involved personally in a study of the flow about a turning submarine body [36, 37]. Some recent work with which I have been involved, studying the flow along a ships chine (an external corner) has demonstrated that the CFD code could not predict the skin friction accurately [32]. There are situations where experiments are needed to verify the codes, which by their nature, require grossly simplified assumptions in order to provide answers.

D.J.Atkins at the 1999 Naval Submarine Symposium [38] described how computational methods could be of benefit to the submarine design process, especially in:

1. the estimation of manoeuvring characteristics and
2. the effects of model mounted sting interference and roll on forces and moments.

It can study a variety of shape changes without the need to build a new model each time. Thus one technique, CFD, complements the other, wind tunnel testing, and both are needed.

6.5 Boundary Layer Control

Since B.A.Toms first published his paper in 1948 on the effects of polymer additives which reduced the skin friction [39], research workers and people involved with ships and especially submarines have been interested in developing the concept, examining alternatives and finding practical solutions.

The Russians even went to the extreme of building an experimental submarine, Beluga, as reported by Dronov and Barbanel at Warship 99 [40]. The injection of the long chain molecules affects not only the friction but also the signature and the wake field. But there are many problems and after ejection the additive quickly becomes diffused so a second ejection slot, circumferentially ringing the hull is required and so on down the length of the boat. The Russians claim enhanced performance which otherwise might be cost prohibitive. The effect of many ringed slots on the structure requires a double hull. Fouling in the slots makes the proposal difficult to maintain at designed efficiency. The volumes and weights involved for the limited time of the benefit in speed and quietness apart from the complications and costs are all at the expense of other demands in the overall design.

H.E.Saunders, a former US naval architect, suggested the idea of reducing drag with lubricants and air bubbles was fallacious [41]. He made this statement in 1957.

In 1999 Moore [42] suggested the boundary layer control (BLC) technology could be improved by better examination of each detail in the process. He pointed out how new understanding showed that the long chain polymers were effective in the buffer layer, a thin zone in the boundary layer above the viscous sublayer and below the highly turbulent outer layer where the polymers are rapidly diffused and ineffective. The work is ongoing, as the potential remains to dramatically decrease friction resistance.

There are proposals for visco-elastic coatings which simultaneously lower the resistance to motion, provide noise insulation, reduce the possibility of detection by non-acoustic means and reduce the shock effects from explosion [9] but no detailed confirmation of these multiple hopes have been found so far in the open literature.

What is shown in [43] are examples of compliant coatings (Fig. 35) with claims that under laboratory conditions transition can be delayed. These coatings at that stage were still very early in the research phase and Gad-el-Hak [44, p133] reports some controversy over the possible benefits.

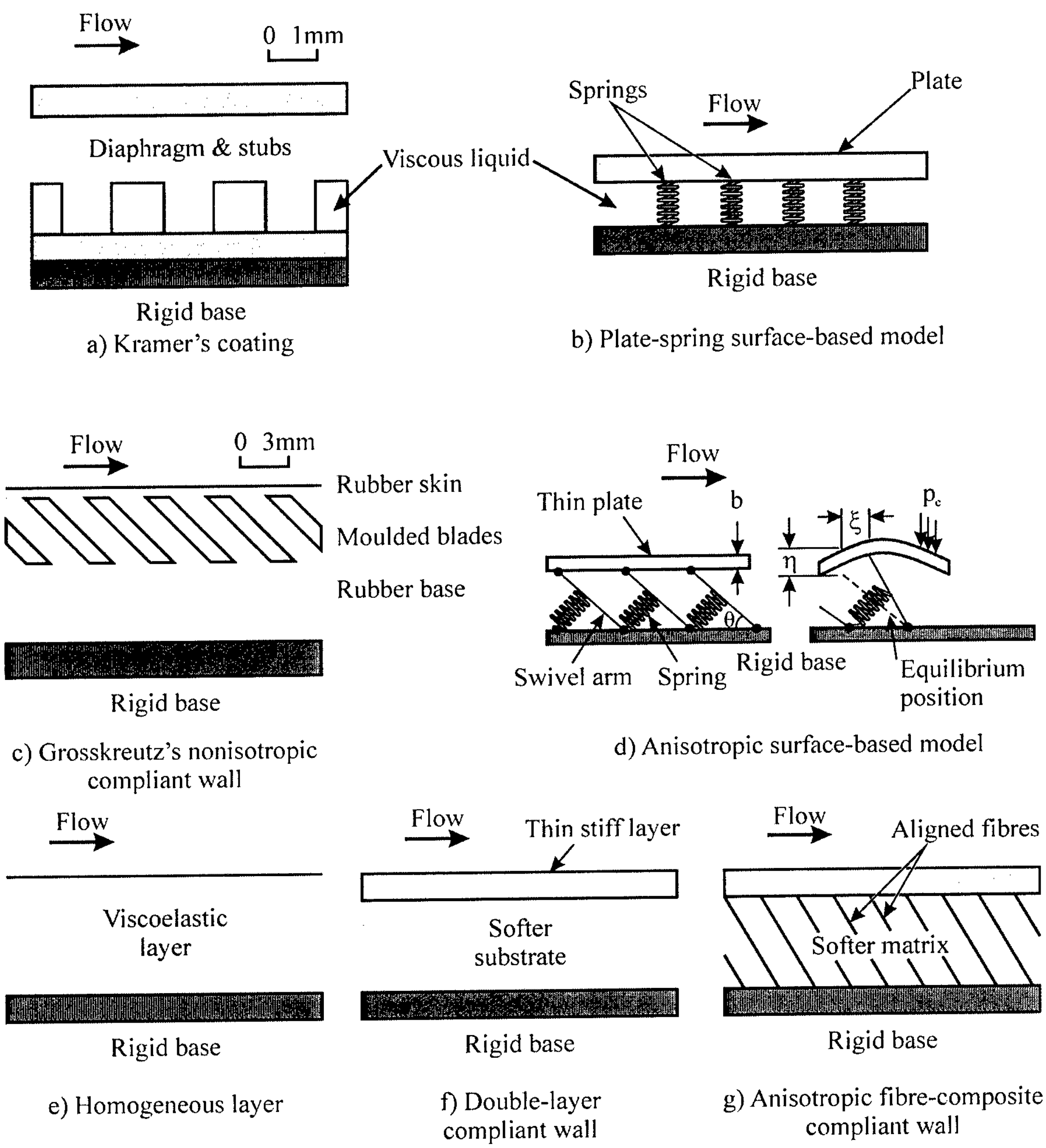


Figure 35. Volume-based and surface-based models of compliant coatings [43].

It is calculated that transition Reynolds number, where the length measurement extends from the leading point on the nose to the transition point may be improved from 2.2×10^6 to 13.62×10^6 by the compliant surface. Based on these numbers when travelling at 5 knots, the transition point on the nose of a submarine like Collins but with a proper ellipsoidal shape would be moved from 1.265m to 6.57m from the leading point. The associated reduction in drag can be calculated. At 20 knots the effect is reduced. Transition on an untreated surface would then take place at 300mm from the forward point. On the

compliant surface, laminar flow would exist for only 1.6m, hardly worth all the effort. There could be no acoustic tiling when it is replaced by a compliant coating. Contrary to the overall claims, Admiral Hervey [14] suggests that synthetic coatings tend to be incompatible with important signature reduction requirements, that is the fitting of anechoic tiles [14, p. 27].

Research workers are also investigating tiny sensors called micro electric mechanical sensors (MEMS) which would involve fitting a large number of devices in panels - up to one million per square metre. These devices are similar to the logic in computer boards and would sense when turbulence might commence and then with control logic apply selective suction to reduce the formation of unstable longitudinal low speed streaks which are created at the beginning of transition. These devices cannot be seen as practical at this stage of development. Gad-el-Hak in his book on Flow Control [44] devotes two chapters on this subject.

In the book edited by Bushnell and Hefner [44], various other means for controlling turbulence are discussed including, micro bubbles, particle injection and others with even less application to the boundary layer flow on a submarine.

At this stage the most promising BLC device would be compliant surfaces, which involve no gadgetry, and may be applied like anechoic tiles. It might then be possible to delay transition over that portion of the nose covering a forward placed sonar. All the interactions on other aspects of the design should be studied.

6.6 Vortex Control

Moore et al. [45] discuss problems in submarines from large vortices. They mention vortices produced by the hull whenever it moves with its axis at an angle to the direction of flow as in a turn be it in the horizontal plane or any other direction. The cross flow generates separation which added to the forward motion ends up as a conical vortex. Two opposing vortices are formed, one below and one above the hull in a horizontal turn.

It has already been mentioned how the fin may interfere with the upper vortex, the vortices are then asymmetrical and this can cause pitching moments.

The subject of body vortices in a turn is under study at the University of Melbourne [36, 37].

Moore et al. mention how the necklace vortex at the base of the sail may become unsteady and interfere with the smooth flow into the propeller. They comment on their intensity.

Tip vortices are created from all lifting surfaces, such as the sail in a turn and control surfaces when active, that is inclined at an angle to the flow.
The vortices created at the aft end of an improperly shaped casing are called turtle-back vortices, which can lead to large changes in the axial components of the flow into the

propeller. This in turn can produce large localised changes in angles of incidence and large unsteady forces.

They then refer to the vortex pattern created behind bluff bodies such as periscopes and masts. When the separation occurs with a laminar boundary layer the pattern of the large vortices is alternate and is known as a Karman vortex street after Theodore Von Karman. Large vibrations can result due to the fluctuating side forces resulting from the asymmetrical flow patterns into an individual vortex before it is shed from the rear of the cylinder to be replaced by a vortex growing from the opposite side.

Their description of what happens at higher Reynolds numbers with separation associated with a turbulent boundary layer is incorrect. Then the size of the separated wake is less and the drag coefficient is about half that with laminar separation.

Finally they mention vortices contained in cavities such as with the MBT and the extremely loud, long distance carrying sounds that can resonate therein. The sound levels created in these cavities can be 20 dB above the normal ambient ocean noise.

They then say there are certain remedies for some of these flows. A small wing mounted above and over the necklace vortex as on the Russian Charlie Class SSGN can reduce necklace vortices. Swept leading edges on the sail reduce the necklace vortex (as does a thinner sail). Tip blowing can reduce the size of tip vortices. Vortex generators suitably placed can reduce the size of vortices created on the main body due to turning. Suitably placed plates can reduce Karman vortex streets, it is claimed.

The essential message from this paper is that vortices represent lost energy and often loud sounds. They need to be understood and minimised when possible. In discussion the authors claim that drag reductions of 30 to 50% can be achieved over submarines where no attention has been paid to proper configuration of surfaces and appendages.

7. Conclusions

1. The history of submarines showed that there were two major advances in their design and capabilities. Both resulted from collecting the best scientific evidence of the time. The Germans produced the Type 21 at the end of World War II. The United States produced the USS Albacore in the 1950s.
2. Design of a submarine is like a jigsaw puzzle and no particular feature should be enhanced without considering its interaction on all other features of the design. Failure to do so can result in a deterioration of the particular desirable feature and the overall design. As with altering the shape of one piece of a jigsaw the design no longer works.
3. Priorities in design need to be clearly stated. At this stage (2004) they would not appear to be much changed from the present role of Collins. However transit time is a

problem and, if possible, needs to be improved. The open literature on priorities in design has been reviewed. The priorities need to be clearly stated by the client.

4. The criteria for best shape are explained and a possible best shape allowing for all present priorities is presented. As initially drawn, the length overall is the same as Collins at 255 feet (77.7m) but the beam has been increased from 25.6 feet (7.8m) to 31.5 feet (9.6m) which allows four decks over portion of the length. The prismatic coefficient is lower at a more efficient value and the draft increased from 23 feet (7.0m) on Collins to a manageable 25.3 feet (7.7m). The next step in the design process would be to reduce the length of parallel mid-body as the greater diameter has increased the displacement beyond that of Collins. Comparably they should be the same. This then requires internal rearrangements and the beginning of the jigsaw puzzle to a new design.
5. It is suggested from all the reading that the most important passive sonar should be placed alone in the nose as with all US submarines. The torpedo tubes are then positioned further aft and angled outwards at about 15 degrees. The suggestion that toppling of torpedoes would result, would apply to a greater extent to tubes arranged at the extremities of a hemispherical nose.
6. With this singular arrangement of the passive sonar the nose shape can then be optimised for best flow conditions and would be ellipsoidal in shape with monotonic changes in longitudinal pressure over and beyond the sonar. It should then maintain its operational capabilities up to the maximum underwater speed of about 20 knots (10.3 m/s).
7. Swedish research shows that the combination of a hemispherical nose with bow torpedo tubes and a passive sonar mounted above the tubes in a deformed bump produces most undesirable flows.
8. The surface finish of the hull is critically important to the resistance of a submarine. The constructors have given insufficient attention to this in the past. The maintenance of a smooth finish, not just the removal of excessive fouling, will pay dividends in more silent operation, lower fuel consumption and greater top speed.
9. The sail should be as narrow as possible to reduce the effects of the necklace vortex and the amount of water contained therein.
10. Greater attention should be paid to the fairing of the sail with the main hull.
11. Sail mounted hydroplanes could be designed with a continuous main spar, fixed forward sections and moving after surfaces as found in some other submarines.
12. Aft mounted hydroplanes might well benefit from having fixed forward portions and moving after surfaces. Their join to the hull needs careful design.
13. A long tube carrying the towed array be deleted and a miniaturised cable led through the fixed forward portion of an aft control hydroplane. Any such change should be examined for its effect on other aspects such as turning circle and stability and control.
14. After wind tunnel and CFD studies, proper streamlining of all masts raised while submerged would return positive benefits and should allow faster transit times. This should prove to be a fruitful area for lowering the resistance and the noise.
15. Flood openings need to be carefully studied in order to reduce drag and noise.
16. Additional shapes such as a casing, need to be smoothly blended into the circular cross-section of the hull. Non-smooth shapes which develop lateral pressure gradients

can lead to the most critical consequences as with Collins where the intense vortices created, exacerbated cracking of the propeller blade. Such mal flows also create strong sounds.

17. Flank and distributed arrays should be arranged so that they blend smoothly (dead smooth) with the hull surface. Despite the desire to maintain them in one plane this should not be allowed to compromise other requirements.
18. The afterbody may need to be a little fuller than ideal in order to accommodate heavy weights in the stern.
19. The propeller may be ducted as this will create less sound and may well be more efficient.
20. It is imperative that wind and water tunnel studies commence on available models and the results compared with CFD studies in order to gain greater understanding of all the detailed contributions to resistance, which add to the total resistance of a submarine. These studies should include masts.
21. Advances in boundary layer and vortex control need to be followed. At this stage the most promising appears to be compliant surfaces which could be applied to the nose in order to delay transition to a position aft of the forward sonar. The effect of this compliant surface on signature and all other interactions should be examined.

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Appendix A: Drag

A.1. Equal Drag on Masts, One Streamlined and the other Circular in Cross-Section

For a streamlined mast the drag coefficient is,

$$C_D = \frac{\text{drag / unit span}}{1/2\,\rho V^2 \text{chord}}$$

Higher values on say a 15% thick shape at the appropriate Reynolds number is about 0.006. So take $C_D = 0.01$ allowing for roughness.

For a circular cylinder the drag coefficient is,

$$C_D = \frac{\text{drag / unit length}}{1/2\,\rho V^2 \text{ diameter}}$$

For a laminar boundary layer $C_D = 1.2$ and for a turbulent boundary layer with a degree of roughness $C_D = 0.6$.

For equal drags,

$$C_{D\,S.L.MAST}\ 1/2\,\rho V^2 \text{ chord} = C_{D\,CYLINDER}\ 1/2\,\rho V^2 \text{ diameter}$$

and so,

$$\begin{aligned} \text{chord} &= \frac{C_{D\,CYLINDER}}{C_{D\,MAST}} \text{diameter} \\ &= \frac{0.6}{0.01} \text{diameter} \\ &= 60 \text{ diameter} \end{aligned}$$

Here the worst case has been compared, a high C_D for a streamlined shape and a low C_D for a cylinder. If the mast suffered a laminar separation, to give equal drag with the streamlined shape, the chord would need to be 120 cylinder diameters. Streamlining shows major advantages.

Notes:

1. For a smooth cylinder as found in laboratory tests, with a turbulent boundary layer, the drag coefficient would be lower (about 0.32) but operational devices usually have a degree of roughness [26, fig. 14, pp. 3-10].

2. It would be of interest to find the drag coefficients of the various masts at full scale Reynolds number both singly and in combination.

A.2. Drag of Snorkel Mast

Assumptions:

1. Length of mast in water = 3.2m
2. Chord of snort mast = 1.1m
3. Thickness of snort mast =0.7m
4. The drag coefficient from Hoerner [26, Fig. 22, p3.12], $C_D = 0.6$
5. The velocity of the snorkel mast,
$$V = 10\text{ knots}$$
$$= 5.15\text{ m/s}$$
6. Density of seawater
$$\rho = 1025.9\text{ kg/m}^3$$

Therefore

$$\begin{aligned}\text{Drag} &= 1/2\,\rho V^2 C_D (\text{length})(\text{thickness}) \\ &= 1/2(1025.9)(5.15^2)(0.6)(3.2)(0.7) \\ &= 18.268\text{ kN}\end{aligned}$$

and

$$\begin{aligned}\text{Power} &= \text{Drag x Velocity} \\ &= 94\text{ kW}\end{aligned}$$

A.3. Streamlined Shape Encasing Snorkel and All Masts Raised When Submerged

Assumptions:

1. Chord of shape = 3 m
2. 15% thickness: chord ratio
3. Velocity of mast as above (10 knots)
4. Worst case drag coefficient $C_D = 0.01$

$$\begin{aligned}\text{Side Area of shape} &= (\text{chord})\ (\text{height of mast in water}) \\ &= (3)(3.2) \\ &= 9.6\text{ m}^2\end{aligned}$$

$$\begin{aligned}\text{Drag at 10 knots} &= 1/2\,\rho V^2 C_D(\text{side area})\\ &= 1/2(1025.9)(5.15^2)(0.01)(9.6)\\ &= 1.306\ \text{kN}\end{aligned}$$

$$\begin{aligned}\text{Power} &= (1.306)(5.15)\\ &= 6.7\ \text{kW}\end{aligned}$$

A.4. Drag and Power of a Single Periscope of Diameter 300mm

The drag coefficient on a cylinder at 10 knots is 0.6 since the Reynolds number is above critical $(> 5\text{x}10^5)$ and boundary layer is turbulent with a degree of roughness.

$$\begin{aligned}\text{Drag of periscope at 10 knots} &= 1/2\,\rho V^2 C_D(\text{frontal area})\\ &= 1/2(1025.9)(5.15^2)(0.6)(0.3)(3.3)\\ &= 7836.5\ \text{N}\end{aligned}$$

$$\begin{aligned}\text{Power} &= (7836)(5.15)\\ &= 40.38\ \text{kW}\end{aligned}$$

A.5. Fixed Tube for Towed Array

Assumptions:

1. Diameter = 300 mm
2. Length = 10 m
3. Average angle of crossflow = 20°
4. Drag coefficient from Hoerner [26, Fig. 18, p3.11] would be 0.07
5. Velocity of 10 knots
6. Seawater density 1025.9 kg/m^3

$$\begin{aligned}\text{Drag} &= 1/2\,\rho V^2 C_D(\text{length})(\text{diameter})\\ &= 1/2(1025.9)(5.15^2)(0.07)(0.3)(10)\\ &= 2.857\ \text{kN}\end{aligned}$$

and

$$\begin{aligned}\text{Power} &= (\text{drag})(\text{velocity})\\ &= 14.7\ \text{kW}\end{aligned}$$

Appendix B: Comments on Design Outline

1. Diesel propulsion is assumed
2. Range, speeds, payloads, depths similar to Collins
3. Improvements to be made wherever possible using Collins as the starting point because this is our only design and construction knowledge base.
4. Shape of boat according to best principles discovered in report. L:B ratio now 8.15:1. A certain amount of parallel mid-body included to give extra deck space and to reduce draft below that of the ideal Albacore shape. Aft of station 68645, the stern shape is the same as Collins. Aft of station 56000, the reduction in area towards station 68645, is more gradual than that on Collins. The greatest overall diameter gives so much more interior volume allowing this less severe reduction with benefits in lower profile (pressure) drag.
5. Ellipsoidal shape on the forebody is constructed in a series of truncated cones (similar to the after sections) from parallel body forward to the beginning of the pressure hull.
6. Forward of this bulkhead (7590), construction would be in fibreglass to achieve smoothest shape over the forward hydrophone. It should then be possible to achieve laminar boundary layer flow over the principle sensor with operation up to service speeds.
7. Smooth profile up to parallel mid-section to be achieved by varying thickness (packing) of tiling. The offset from the smooth shape is not large on the truncated cones.
8. Torpedo tube outlets are now located aft of principle sensor. This arrangement must be carefully checked to ensure there is no boundary layer transition over the sensor. If there is a problem then the nose may be lengthened by one or two metres. In the latter case the principle sensor is also moved forward. This extended nose is shown. The vertical arrangement of three tubes per side is as arranged on Oberon so should present no problems.
9. Torpedo room extended aft by 3m (c.f. Collins) because watertight tubes no longer extend forward beyond bulkhead. Figure 28 shows a similar arrangement on a British submarine. The loading of torpedoes from shore and into the tubes needs a careful study but is similar to that of Collins.
10. Casing has been lowered to 1m above pressure hull reducing the troublesome effect of the turtle back. Smooth, continuous cross-profile of join to pressure hull with no acoustic reflection and drag producing internal corners is now a feature. Certain items such as the escape trunk need to be lowered. The towed array windlass still fits under, but if it is included then surely it will be miniaturised.
11. The active sonar array housed within the cylindrical passive bow array on Collins, from the hydrodynamic consideration, is better positioned further aft. HMS Trafalgar and similar vessels have this device positioned closer to the sail; it has been tentatively shown just forward of the foremost bulkhead in the new profile.

12. As the arrangement with the larger diameter leaves some unallocated internal volume it would be possible to shorten the vessel with some rearrangement. For a direct comparison with Collins, the displacements should be the same.
13. The shape and arrangement as proposed is but a first tentative step along the path to a new submarine. It is so preliminary that the normal hydrodynamic calculations of displacement, longitudinal centre of buoyancy, centre of gravity, wetted surface area and so on, have not been calculated, let alone those of resistance and powering, and dynamics and control.
14. The greater diameter means heavy weights such as batteries will be positioned further below the CB so the stability margin will be improved.
15. The question of revised shape of control surfaces has not been included as there are matters yet to be resolved and until this occurs, the X-shaped aft controls are featured. Likewise the position of the winding mechanism for the trailing array is as on Collins but reduced in size.

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19. ABSTRACT

The history of submarines shows there were two significant advances in the performance of submarines, which occurred after full scientific studies were undertaken. The first was by the Germans at the end of World War II when they produced the Type 21, which could have upset the balance in the U-Boat campaign if it had arrived earlier. The second was by the US Navy with Albacore which had a submerged speed of over 30 knots. To neglect full scientific studies would be a serious mistake in the design of any future replacement submarine. Design is shown to be like a jigsaw puzzle where altering one piece requires alterations in all surrounding features to make a workable complete design. The basis of improved hydrodynamic features is discussed. A new nose shape is presented which should improve the performance of the forward passive sonar up to operational speeds. Other major sources of resistance may be improved. It is proposed a first major step should be to establish the detailed performance of Collins using wind tunnels and computational fluid dynamics which will serve as the comparative foundation for any new design.

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